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APPLICATION OF THE VIKOR METHOD FOR SELECTING THE PURPOSE OF RECULTIVATED TERRAIN AFTER THE END OF COAL MINING

Radmila Gaćina✉, Sanja Bajić, Bojan Dimitrijević, Tomislav Šubaranović, Čedomir Beljić, Dragoljub Bajić

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Abstract

Surface mining of coal has a negative impact on the environment that needs to be prevented, reduced, controlled, monitored by applying the management of technological processes of technical and biological recultivation after the end of exploitation works. The paper deals with the problem of multi-criteria decision-making in the process of selection of indicators that have an impact on the choice of purpose of recultivated terrain after the end of coal mining. The considered reclamation solutions represent possible alternatives. Degraded areas need to be returned to their original purpose, they should be in the function of environmental protection of the natural environment and settlements near this location. In addition, various criteria and sub-criteria that affect the choice of the most favourable solution were defined and analyzed. The final decision on land use after exploitation was made based on mathematical calculations using the multi-criteria VIKOR method.

Key words: reclamation, coal, sustainable development, multi-criteria decision making, VIKOR method

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Introduction. Natural mineral resources are very important for people's life, economic construction, and social development, of which the exploitation of coal as a fossil fuel and its preparation and processing play the most important part in the energy economic structure of the Republic of Serbia. Surface mining of coal is often accompanied by environmental damage due to the large areas of land it occupies. If the exploitation process is not managed properly, it can lead to soil erosion, soil and water pollution and alternation of geodiversity. Therefore, mining companies are legally obliged to rehabilitate land and recultivate surface mines and landfills in the post-exploitation phase as an environmental obligation within their business. Reclamation works after mining exploitation require human intervention. Allowing nature to restore itself is not an option, and reclamation works are prescribed by law in the Republic of Serbia. Reclamation works aim to improve the land after exploitation, make it more productive and convenient for use.

Groups of multi-criteria decision-making methods, sometimes called decision support techniques, are considered very common and important decision-making tools in both business and engineering. These methods work in a wide range of civilization interaction with natural and human subjects [1, 2]. Multicriteria decision making is well defined, established and comprehensively studied as a branch of research where methods deal with multiple conflicting evaluation criteria to select one alternative or rank alternative solutions to a given problem.

From a historical point of view, during the second half of the 19th century, the most applicable methods were determined: ELECTRE, AHP, VIKOR, TOPSIS, PROMETHEE, as well as others from the same group of methods. As the area of their application expands, the methods of multi-criteria decision making are considered very different in their approach, but they are used in a similar context [3, 4].

Mine reclamation is the process of land rehabilitation after coal mining. What the industry refers to as reclamation is the process of restoring and/or improving land after surface mining [5]. The reclamation plan includes the study of geology, pedological soil characteristics, water resources, flora and fauna. Reclamation of surface coal mines returns the soil after exploitation to a natural or even better economically usable state.

Mine reclamation can create useful, new environmental landscape units for a variety of purposes, ranging from restoring productive ecosystems to creating industrial and urban environments.

Practices related to coal mine reclamation have improved significantly in recent decades. Although the primary purpose of a coal mine reclamation plan is usually to minimize the impact on the local environment after mine closure. Today, reclamation plans can involve much more than simply returning a mining site to its natural state. In the history of mining operations and mine closures, there have been too many examples of post-mining lands that were not properly cared for.

Ensuring the required quality of reclaimed terrain is one of the indicators of the level of surface exploitation in relation to modern ecological requirements and set standards [6]. The intended purpose of the terrain dictates the content and level of normative requirements. Normative requirements of reclamation related to agriculture and forestry are reduced to the creation of a useful biological layer on the surface of the terrain that ensures the growth and development of plants. If the purpose of the terrain is aquatic, it is necessary to fulfill certain technical-technological, geotechnical and geomechanical conditions for the performance of hydrotechnical works. For construction and industrial facilities, it is necessary to create areas that favour the placement of facilities. If the terrain is recultivated and spatially planned for recreational needs, it is necessary to fulfill several norms that are prescribed for the formation of rest areas.

Numerous previous studies show that new agricultural, forest, aquatic, meadow and other ecosystems can be created on such degraded areas [7-10]. Post-mining land-use prescribes the methods, the measures and the costs of mine reclamation; a major implicit goal of mine reclamation is to determine an after-use option. Bangian et al. [7] using fuzzy AHP developed a model for optimum post-mining land use for open pit area Sungun copper mine in the Northwest of Iran where Forestry–lumber production was defined as the optimum post-mining land. Bascetin [8] formulated a model based on AHP for selecting the optimal method and based on the global priority weights of the five land reclamation methods, determined that the method of planting trees/forest land has the most points. Soltanmohammadi et al. [9], applied the AHP method to calculate global weights of the attributes through pairwise comparison matrixes and applied ELECTRE to analyse the provided framework. The use of pasture and industrial post-mining land were selected as effective alternatives. Soltanmohammadi et al. [10] developed a process for post-mining land-use determination in which a Mined Land Suitability Analysis (MLSA) framework is utilized. The MLSA is based on the LSA frameworks and is composed of fifty numbers of most significant attributes in the post-mining land-use decision making. In this study, combination of AHP and TOPSIS techniques helped to determine a preference ranking list for possible post-mining land uses of a hypothetical mined land and the industrial land-use was chosen as the most suitable post-mining land-use.

Reclamation is a complex process encompassing mining-technological, engineering agricultural and forestry procedures that are undertaken with the aim of transforming industrially degraded land into a state suitable for agriculture and forestry, recreation, fishing, construction of facilities of various purposes and other goals [11-13]. In general, reclamation implies the re-establishment of new plant and animal communities in areas degraded by coal mining.

Worlanyo et al. [14] in their paper evaluate the economic and ecological impact of land renewal and use after recultivation and divide the impact into three categories: economic, ecological and social. Worden et al. [15] in their

work, set up a set of fifty spatial clusters for quantitative data analysis, bringing decisions down to the regional level, allowing stakeholders to look at the picture more broadly – covering larger areas of land and ecological habitats.

Material and methods. By choosing alternative solutions for land use after the end of mining exploitation and recultivation, it fits in into the previously outlined goals of spatial planning and the use of the landscape after lignite mining. For this reason, it is desirable to cooperate with the appropriate local self-government bodies for detailed planning, design and arrangement of the space after exploitation. Figure 1 shows the flow of solving the decision-making problem and ranking the alternatives, and it consists of the following several steps:

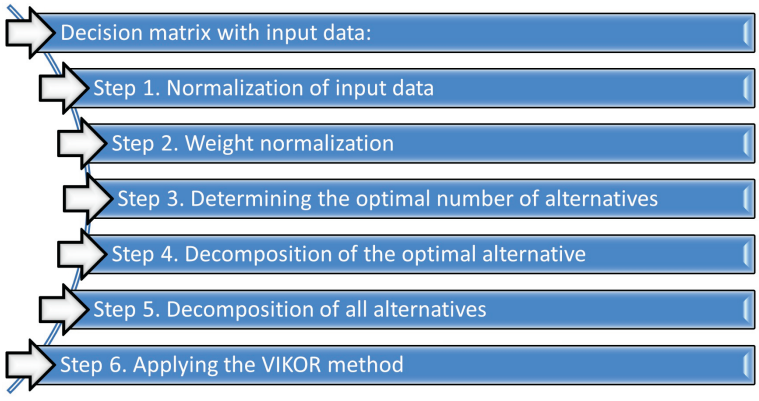


Fig. 1. The flow chart for solving the problem of deciding on an alternative solution for the purpose of the land after reclamation

VIKOR is a multi-criteria optimization method developed by Opricović in 1980, suitable for solving various decision-making problems. It is particularly suitable for situations where quantitative criteria prevail. The name VIKOR appeared in 1990 as an abbreviation of: Multi-criteria optimization and Compromise Solution. The VIKOR method determines a compromise solution that is closer to the ideal and ranks the alternatives based on it [16].

1. First, the alternatives are determined and the relevant criteria for the evaluation of the alternatives are defined.
2. The most convenient way to describe the problem of alternative ranking is the decision matrix, which is shown in the following way on a concrete example:

	C_1	C_2	C_3	C_4	C_5
A_1	X_{11}	X_{12}	X_{13}	X_{14}	X_{15}
A_2	X_{21}	X_{22}	X_{23}	X_{24}	X_{25}
A_3	X_{31}	X_{32}	X_{33}	X_{34}	X_{35}
A_4	X_{41}	X_{42}	X_{43}	X_{44}	X_{45}
A_5	X_{51}	X_{52}	X_{53}	X_{54}	X_{55}

Here X is the performance, in relation to alternatives and criteria.

3. The most favourable values for all criteria are determined (the highest value for maximization, the lowest for minimization or the target value for criterion $j : T = \{T_1, T_2, T_3, \ldots, T_j, \ldots, T_n\}$ = most desirable element x_{ij} or target value for criterion j, where x_{ij} represents the performance of the i-th alternative in relation to the j-th criterion, where m is the number of alternatives and n is the total number of criteria.
4. Determine the relative importance of the criteria, whereby the following applies:

$$\sum_{i=1}^{n} w_i = 1, \tag{1}$$

5. Determine the weight value v. v should depend on the number of criteria (n): $v = 0.5$ for $n \leq 4$, $v = 0.6$ for $5 \leq n \leq 10$, $v = 0.7$ for $n \geq 11$. In this case, $v = 0.6$ is adopted
6. Calculate the values of metrics S_j and R_j.

$$S_j = \sum_{i=1}^{n} w_i = \frac{f_i^* - f_{ij}}{f_i^* - f_i^-} \tag{2}$$

$$R_j = \max\left(w_i \frac{f_i^* - f_{ij}}{f_i^* - f_i^-}\right) \tag{3}$$

f_i^* and f_i^- – maximum and minimum values of the criteria function for all variants, respectively: $f_i^* = \max\limits_j f_{ij}$ and $f_i^- = \min\limits_j f_{ij}$ $(i = 1, 2, \ldots, n)$

S_j represents the measure of deviation, which expresses the request for maximization of group utility, R_j represents the measure of deviation, which expresses the request for minimizing the maximum distance of the alternative from the ideal.

7. Calculate the values of the total ranking index of the alternatives.

$$Q_j = v\frac{S_{j-S^*}}{S^- - S^*} + (1 - v)\frac{R_j - R^*}{R^- - R^*} \qquad (j = 1, 2, \ldots, J), \tag{4}$$

where $S^* = \min\limits_j S_j$, $R^* = \min\limits_j R_j$, $S^- = \max\limits_j S_j$, $R^- = \max\limits_j R_j$, S^* and R^* are the best limits of metrics S_j and R_j, and S^- and R^- are the worst limits of metrics $S_j$and R_j, or

$$Q_j = vQS_j + (1 - v)QR_j. \tag{5}$$

8. Complete three rankings of alternatives based on the values of S_j, R_j and Q_j. The best alternative, ranked according to the compromise ranking, is the one with the lowest value of Q_j.

Case study Drmno. The surface exploitation of coal in the Kostolac coal basin leads to permanent damage to the natural ecosystem because agricultural and forest areas are degraded.

The Kostolac mining and energy basin is located about 90 km east of Belgrade, i.e. 12 km north of Požarevac. Drmno is geographically located in the municipality of Požarevac, in the Braničevo district, in Serbia (Fig. 2). The external disposal site of the open pit Drmno is located east of the open pit Drmno, north of the village of Bradarac, and covers an area of 200 ha, covering the cadastral municipalities of Bradarac and Kličevac. During that time, 75 000 000 m^3 of tailings were disposed of. With the development of the landfill, work on the technical and biological reclamation of the southern part of the I and II landfill, the floor towards the village of Bradarac, was started [17].

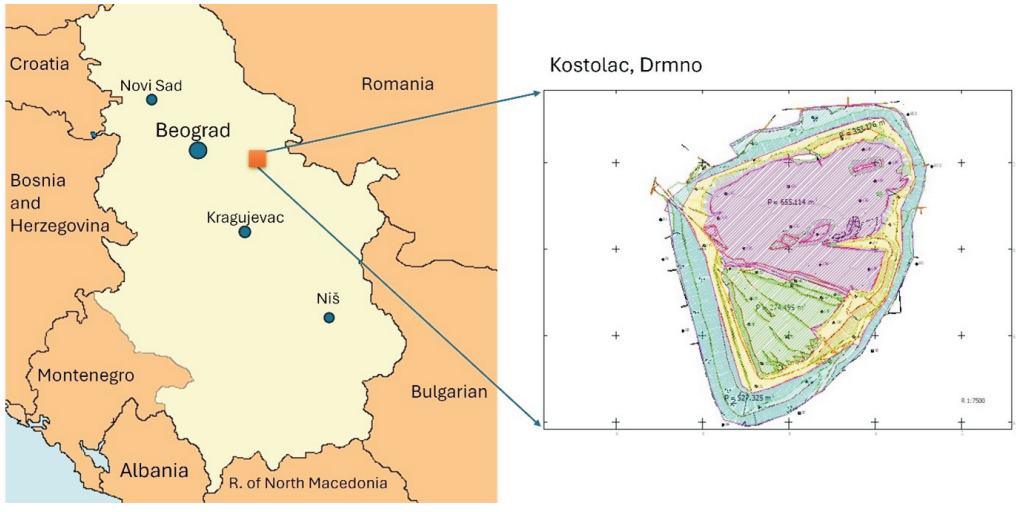


Fig. 2. Geographical location of the Drmno – Kostolac External Landfill (modified [18])

So far, on the researched area of recultivation of the Drmno External Landfill, the basic strategic goal in revitalization and recultivation of space, as well as nature protection, has been realized. This reduced the unfavourable impact of coal exploitation and processing on the condition of the surrounding agricultural land, forest, water, air, wildlife, as well as other natural and socio-economic living conditions. Along with fulfilling the basic strategic goal of recultivation, effective measures were taken for the gradual realization of constant and noticeable improvement of ecological, economic and ambient-landscape features in the entire area.

The planting of forest plantations in the period after exploitation will have an ameliorative effect on the substrate by increasing its biogenicity and starting pedogenetic processes, and in combination with the grass cover that appears spontaneously, it will prevent the development of erosion and stabilize the slope of the

landfill. With its leaf mass, it will play a significant role in the filtration of air pollutants (ash and dust from active mines), and the protection of surrounding settlements.

Once established, the processes of circulation of matter and energy in the newly established ecosystems, later lead to the complexity of the vegetation cover. Practice has shown that with the development of plantations over a certain period of time, there is a spontaneous and gradual settlement of resistant species from the surrounding natural vegetation, which biologically stabilizes this ecosystem. The levelled surfaces of the mine are intended for the organization of agricultural production on the deposol, which would lead to the formation of anthropogenic soil capable of regular production through two phases of agricultural recultivation. The biological reclamation of the "Drmno" surface mine would gradually, through several stages, lead to the revitalization of the landscape, the complexity of the formed eco- and agro-ecosystems, and a significant improvement in the quality of the environment in this area. The recultivation of the tailings disposal site is carried out by agrobiological recultivation and afforestation in accordance with the final vision of the organization of the space after the exploitation of coal.

Results presentation and discussion. To solve the problem of choosing an alternative after recultivation of the deposit, the following alternatives were given as potential: A_1 – *Agriculture – arable and vegetable growing*, A_2 – *Agriculture – fruit growing and viticulture*, A_3 – *Forestry*, A_4 – *Recreation area (sports-recreational complex)*, and A_5 – *Industrial zone – wind generators*. By determining the criteria on the basis of which decisions are made, we set the basis for choosing an alternative solution for the purpose of the terrain after recultivation. The criteria are: K_1 – *Amount of investment per unit area*, K_2 – *Investment period – investment time*, K_3 – *Time for return of invested funds*, K_4 – *Adaptability and compatibility of the reclamation solution with the environment*, and K_5 – *Social, economic and ecological importance of reclamation for the local community* [18].

A decision-making matrix was set up according to the given criteria. After setting up a set of criteria, it is necessary to evaluate them. Criterion minimization and maximization are performed. The Saaty scale [19] was used to evaluate the alternatives in relation to the criteria. The relative significance of the criteria was determined, where $w_i = 1$. The value of weight v was determined. Given that the number of criteria in this case is $n = 5$, and the weight value v depends on the number of criteria, we adopt $v = 0.6$ for $n \geq 5$. The values of metrics S_j and R_j are calculated. Then the total ranking indexes of alternatives QS_j and QR_j were calculated, where: $QS_j = (S_j - \min S_j)/(\max S_j - \min S_j)$; $QR_j = (R_j - \min R_j)/(\max R_j - \min R_j)$, as well as the value Q_j which represents a linear combination of metrics S_j and R_j. A ranking of alternatives was performed based on the values of S_j , R_j and Q_j and a proposal for the final solution was given. Table 1 shows the calculations.

This paper presents the multi-criteria method VICOR, tested and validated

Table 1

Quantified decision matrix and criteria maximum, intermediate values $(f_{i\max} - f_{ij})/(f_{i\max} - f_{i\min}) * w_i$, values of S_j and R_j, Intermediate results (QS_j and QR_j) and ranking of alternatives (Q_j)

Eligibility criteria / Alternatives	k_1	k_2	k_3	k_4	k_5
A_1	9	5	3	9	3
A_2	7	3	5	5	1
A_3	5	1	1	7	5
A_4	3	7	7	1	7
A_5	1	9	9	3	9
Extr	max	max	max	max	max
f^*	9	9	9	9	9
f^-	1	1	1	1	1
D	8	8	8	8	8
Intermediate results $(f_{i\max} - f_{ij})/(f_{i\max} - f_{i\min}) * w_i$					
A_1	0	0.5	0.75	0	0.75
A_2	0.25	0.75	0.5	0.5	1
A_3	0.5	1	1	0.25	0.5
A_4	0.75	0.25	0.25	1	0.25
A_5	1	0	0	0.75	0
Values S_j and R_j, intermediate results (QS_j and QR_j) and ranking of alternatives (Q_j)					
Alternatives	S_j	R_j	QS_j	QR_j	Q_j
A_1	2	0.75	0.166667	0	0.1
A_2	3	1	0.833333	1	0.9
A_3	3.25	1	1	1	1
A_4	2.5	1	0.5	1	0.7
A_5	1.75	1	0	1	0.4

on the example of the reclamation of the Drmno External Landfill, Kostolac. This modern tool allows the decision maker to set priorities to make the best decision. Based on the performed calculations according to the presented results, the final solution is alternative A_1 – agriculture. The order of the other alternatives is A_5, A_4, A_2 and, as the least favourable solution, A_3. The mentioned areas are designed in such a way as to ensure an ecologically favourable fit of the given areas into the existing environment.

In this way, a more objective view of the problem and its more efficient solution is achieved. The diagram of the optimal alternative solution for the land use of the Drmno External Landfill is shown in Fig. 3.

Conclusion. Land reclamation after surface coal mining is an integral part of the system of coal mining and use. The choice of land use after the closure of the

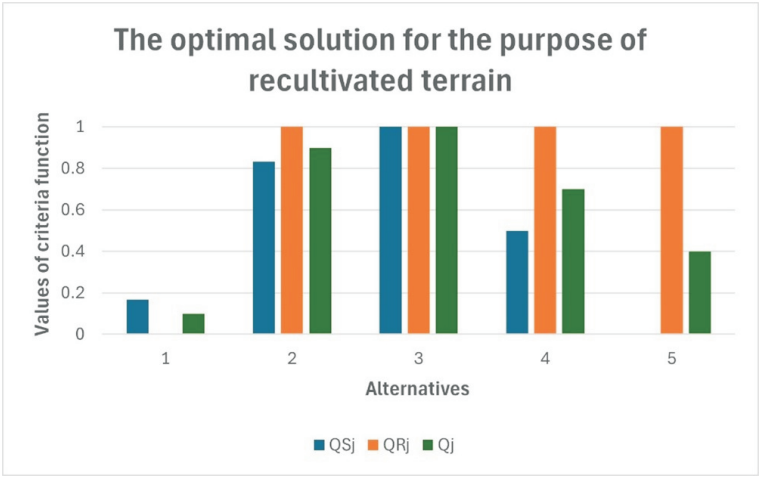


Fig. 3. Diagram of the optimal alternative solution for the land use of the recultivated external landfill Drmno

mine is a difficult decision, which is further complicated by the various parameters that must be considered to provide the local community with a sustainable plan for the development and use of the land after mining exploitation. Conventional methods used for reclamation planning are characterized by a lack of field data integration and long-term analysis.

Multi-criteria optimization methods are widely used in various spheres of life, science, and professional practice. Many multi-criteria optimization methods have been developed, and each of them aims to help the decision maker in solving complex engineering problems. In this paper, we propose the use of the VIKOR method for the assessment of land use after coal mining, respecting technical-technological, economic, social, and ecological criteria. The proposed methodology was applied to the reclamation of the Drmno surface mine external landfill, which is in the Kostolac coal basin, in the Republic of Serbia.

The application of the VIKOR method shows that the decision support system allows the mining company to efficiently determine the specific land use (agricultural land, forest, recreation area, industrial zone, etc.), which is considered the most suitable for each segment of the studied environment. From an economic point of view, this model helps to reduce costs and increase profits, but it is also necessary to reduce the impacts of mining on the external environment, to develop the trust of the local population in mining activities, and to choose the most favourable method of technical reclamation. A combination of alternatives $A_1 + A_5$, agriculture (arable and vegetable growing) and the initial phase of the construction of seven wind generators that are part of the Kostolac wind park, was applied at the location. In the area of Drmno covered by agricultural reclamation, the following crops were planted: alfalfa, wheat, barley, and sugar beet. The

implementation of biological reclamation contributes primarily to the protection of the environment, the development of stable ecosystems and the improvement of the ambience.

The Kostolac wind farm represents an effort to move away from coal and symbolizes the commitment to reduce reliance on fossil fuels, decarbonize the economy, and embrace renewable energy sources. About 30 000 households will benefit directly from this wind farm, not only due to the production of electricity, but also environmental protection and reduction in the use of fossil fuels.

Land reclamation offers ecological, economic, and social benefits and is extremely important for sustainable agricultural production, as well as for the sustainable development of industrial mining companies. Furthermore, over time land reclamation will offer greater overall benefits to this mining area.

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Faculty of Mining and Geology, University of Belgrade,
7 Djusina St, 11 000 Belgrade, Republic of Serbia
e-mails: radmila.gacina@rgf.bg.ac.rs, sanja.bajic@rgf.bg.ac.rs,
bojan.dimitrijevic@rgf.bg.ac.rs, tomislav.subaranovic@rgf.bg.ac.rs,
cedomir.beljic@rgf.bg.ac.rs, dragoljub.bajic@rgf.bg.ac.rs