sustainability

MDPI

Article

A Novel Hybrid Fuzzy Multiple-Criteria Decision-Making Model for the Selection of the Most Suitable Land Reclamation Variant at Open-Pit Coal Mines

Bojan Dimitrijević [1], Tomislav Šubaranović [1], Željko Stević [2,3,*], Mohamed Kchaou [4], Faris Alqurashi [4] and Marko Subotić [3]

[1] Faculty of Mining and Geology, University of Belgrade, 11000 Belgrade, Serbia; bojan.dimitrijevic@rgf.bg.ac.rs (B.D.); tomislav.subaranovic@rgf.bg.ac.rs (T.Š.)
[2] School of Industrial Management Engineering, Korea University, Seoul 02841, Republic of Korea
[3] Faculty of Transport and Traffic Engineering Doboj, University of East Sarajevo, 74000 Doboj, Bosnia and Herzegovina; marko.subotic@sf.ues.rs.ba
[4] Department of Mechanical Engineering, College of Engineering, University of Bisha, Bisha P.O. Box 001, Saudi Arabia; kchaou.mohamed@yahoo.fr (M.K.); fars421@hotmail.com (F.A.)
* Correspondence: 172317@korea.ac.kr or zeljko.stevic@sf.ues.rs.ba

Abstract: The expansion of the open-pit exploitation of mineral raw materials, and especially the energy resources of fossil fuels, makes open-pit coal mines spatially dominant objects of large mining basins. Exploitation activities are accompanied by negative ecological impacts on the environment, which requires the integral planning, revitalization, reclamation, and rehabilitation of the disturbed area for human use in the post-exploitation period. The post-exploitation remediation and rehabilitation of open-pit mining areas and disposal sites, i.e., space disturbed by mining activities and accompanying facilities, are complex synthetic multidisciplinary multiphase engineering project tasks. In this paper, a hybrid fuzzy MCDM model (Multiple-Criteria Decision-Making) was developed for the selection of a reclamation solution for the Tamnava-West Field open-pit mine. IMF SWARA (Improved Fuzzy Stepwise Weight Assessment Ratio Analysis) was applied to define the weights of 12 criteria of different structures used in the evaluation of reclamation solutions. The Fuzzy ROV (Range of Value) method was applied to select the reclamation solution from a total of 11 solutions previously obtained using a process approach. The results of the hybrid IMF SWARA—Fuzzy ROV model show that forestry is the best solution for the Tamnava-West Field open-pit mine. After the results had been obtained, verification analyses of the proposed model were performed and the best stable proposed reclamation solution was determined.

Keywords: reclamation solution; open-pit mining; environment; IMF SWARA; fuzzy ROV

Citation: Dimitrijević, B.; Šubaranović, T.; Stević, Ž.; Kchaou, M.; Alqurashi, F.; Subotić, M. A Novel Hybrid Fuzzy Multiple-Criteria Decision-Making Model for the Selection of the Most Suitable Land Reclamation Variant at Open-Pit Coal Mines. *Sustainability* **2024**, *16*, 4424. https://doi.org/10.3390/su16114424

Academic Editor: Peng Li

Received: 4 April 2024
Revised: 17 May 2024
Accepted: 20 May 2024
Published: 23 May 2024

1. Introduction

Mining pit exploitation is accompanied by a negative ecological impact on the environment, which creates an obligation to continuously complete the planning, revitalization, reclamation and rehabilitation of a disturbed area in the period after exploitation. The post-exploitation remediation and rehabilitation of open-pit mining areas and disposal sites, i.e., space disturbed by mining operations, represent a very complex multiphase engineering problem. Based on the application of decision-making and management theory, it is possible to efficiently solve the problems of applying these phenomena to the processes of technical and biological reclamation of areas and analyzing their general impact on environmental factors.

The reclamation planning process through all phases of open-pit mining development has three levels, namely, preliminary, operational, and final, and can be applied both to new open-pit mines and to open-pit mines in operation for which this has not been done before. Numerous examples of the scenic, natural, and cultural attractiveness of post-mining land encourage the mining sector to create new environmental values and potentials, as well as new conditions for environmental protection. Post-mining land with its landscape generally becomes a natural part of the region and is no longer a place of previous exploitation [1]. Many closed mines have become forests, agricultural lands, and nature reserves. Technical reclamation is a common approach used in post-mine sites and is even a mandatory practice in some regions due to legislation in many countries [2].

The purpose of this research is to analyze a real case study of an open-pit coal mine that is viewed as a basis for experimental analysis to select a reclamation type and appropriate rehabilitation. This process modeling of a unified reclamation system includes a total of 20 alternative solutions for designing the reclamation content (which are modeled through 11 possible solutions in this particular case) and rehabilitation of the post-exploitation area of the Tamnava-West Field open-pit mine and disposal site.

The aim of this paper is the development of a hybrid IMF SWARA—Fuzzy ROV model, for the first time in the literature, to select the best reclamation solution from a set considered for the Tamnava-West Field open-pit mine. The defined aim reflects a twofold contribution from the aspect of the proposed methodology and from the professional aspect, which implies a sustainable relationship with the environment. The IMF SWARA method is used for the calculation of the importance of criteria based on expert analysis and the preferences of experts. Due to the fact that this method belongs to subjective methods for determining criterion weights, in this study, we consulted only experts with a minimum of 15 years of field experience, who have high performance, high skills, and enough knowledge to assess the mutual comparison of criteria. IMF SWARA represents an appropriate and precise tool for determining criterion weights due to its procedure and the fact that experts first need to sort criteria. After that, the experts only compared two criteria. In this way, the IMF SWARA method, compared to other methods for calculating criterion weights, is a very acceptable tool for experts. Also, compared to other methods, the number of total criteria is not limited and there is no need to form a multiphase hierarchical structure as it is mandatory in the AHP (Analytic Hierarchy Process) method. The Fuzzy ROV method represents a simple but precise tool to sort variants according to a multiphase normalization process.

Apart from the mentioned motivation, aims and purpose, the main research questions should be defined.

(1) Is the problem of implementing reclamation solutions in vast areas degraded by coal exploitation evident in Serbia today?
(2) How can we define all potential problems and potential solutions, and how can parameters be defined to fully represent the current state of open-pit coal mining?
(3) Which model can provide a comprehensive analysis and give positive results in practice?

The answers to these research questions will be supported by the findings presented in this comprehensive study model, aiming to satisfy all local requirements for the reclamation of open-pit coal mining areas and to follow sustainable development goals. In Serbia, the problem of implementing reclamation solutions in vast areas degraded by coal exploitation is currently evident. We recognized gaps in practice and, in this study, all necessary input indicators which have influence on sustainable development are addressed. Also, a large set of potential solutions was created based on experimental measurement and using an engineering process approach. Finally, we created an integrated fuzzy model which treats uncertainty in a precise way and enables optimal results. The verification of the feasibility of multiple-criteria decision-making models as demonstrated in this paper, yielded positive results in practice at the Tamnava-West Field mine and confirmed the advantages in ranking the given alternatives.

After the introductory details, this paper is structured into the following sections. Section 2 provides a review of the literature with a focus on recent studies. In Section 3, a decision-making algorithm and the steps of the Fuzzy ROV and IMF SWARA methods are presented. Section 4 provides a description of potential reclamation solutions and the criteria based on which they are evaluated. In this section, the evaluation procedure and the results obtained are also presented. Section 5 refers to verification tests and, finally, Section 6 to concluding considerations.

2. Review of the Literature

Due to specific and very rigorous legislation that prescribes procedures, conditions, competences, and responsibilities, large degraded areas have been successfully restored in many countries. In the area of the Midwest of the USA, farms, which were brought to a state of productivity as before the exploitation of coal by means of agromelioration measures, were established. In recent times, there is often a commitment to the restoration of natural wild habitats. The reclamation technique which turns post-exploitation areas into wetlands is becoming particularly popular [3]. In Great Britain, specific laws regulate the aspect of planning and rehabilitation, separately for England and Wales, and separately for Scotland. A permit to open a new open-pit mine is issued by the National Coal Board (NCB), whereby a contract is concluded with the mining company [4]. In the application of project management principles for reclamation at the sites of old mining pits, the case of Thoricos Bay in Lavrion, Greece, is given as an example of industrial zone rehabilitation and the reclamation of an abandoned and closed area of mining exploitation [5,6]. For the analysis of ecological risk, options for risk isolation and minimization were selected, utilizing a reclamation scheme, while special additional measures were applied in areas of high-sulfide waste. The application of mining technologies, which includes the removal of tailings and the methods of their disposal on waste heaps, as well as the formation of open excavations, has an impact on habitat conditions in areas that have undergone land reclamation [7–9]. China, the USA, and India are taking a leading role in researching the restoration of coal mining sites using modern technologies. Miners in Polish mines carry out reclamation and land rehabilitation using mining skills after the period of exploitation. The works are performed according to a high European standard, so that the land can be used for agriculture or forestry, including recreational activities [1]. An analysis of the existing 5000 contaminated sites in Germany revealed 159 closed open-pit mines, 122 tailings (with ash or lignite), 120 sedimentation facilities, and 9 thermal upgrading plants. The study showed that more than 8.2 billion euros had been spent on lignite rehabilitation by 2008 [10]. Brownfields in France represent contaminated sites where built-up (agricultural, port, industrial, service, etc.) land has been temporarily or permanently abandoned after the cessation of mining activities and which has been put back into use. About 200,000 former industrial sites and about 200 former mines have become brownfields [11]. Based on research conducted at five different pits of the Zhangji coal mine (China) over a period of 11 years, the concept of dynamic subsidence reclamation (DSR) was implemented to evaluate whether DSR could improve both the environmental and socio-economic conditions for post-mining land use by traditional reclamation (TR) or TR-modified (TR(MOD)) reclamation [12].

Based on the research conducted in the High Groundwater Coal Basins (HGCBs) in the eastern China plain at seven areas in Pei county, the study proposed an integrated model for the simulation and optimization of post-mining land use structures. Different scenarios of land use structure in relation to the depth of subsidence were developed in order to determine the optimal collapse depth [13].

The preservation of mining heritage with the aim of making the region more attractive implies the revitalization of facilities after mine exploitation. Studies in Spain, Poland, and Great Britain show that the revitalization and attractiveness of the locations are regulated through legal regulations. This research shows that land lease contracts could contain an obligation to re-stabilize or return the exploited land to its original state of protected environment. Regardless of legal conditions, revitalization measures are being implemented with positive effects at the Gold Mine in Zloty Stok, La Tortilla Mine in Linares, and King Edward Mine, an old mining site in Cornwall [14].

Many coal mines are included in programs of sustainable development, economic support to regions and local communities, environmental restoration, etc. Mining is not related only to exploration and exploitation, but also considers environmental responsibility to protect environmental sustainability [9,12,15,16]. Legal, social, and environmental requirements for complex mining operations are fully integrated into the mining and reclamation plan, while addressing sustainable development and engineering analyses will result in the optimization of mining operations. This systemic approach provides economic and environmental sustainability, the protection and restoration of the environment, and the efficient and effective justification of mining and reclamation. A study has shown that the coal exploitation designer must align legal, environmental, and sustainability goals with traditional mining parameters [17]. A similar approach is given by the National Coal Board (NCB), whereby a contract is concluded with a mining company [4].

Research in Indonesia conducted to analyze the ideal implementation of coal mine reclamation found that, after mining, the land is often left dry with large voids that are prone to flooding and soil erosion. It was found that 70.59% of land reclamation programs in Indonesia aim to reforest mining areas into secondary forests. The implemented types of reclamation are aquaculture, urban forests, park playgrounds, sports parks, livestock farms, and fauna conservation ecotourism. A new reclamation approach called eco-habitat was also developed. The reclamation process should be carried out using an eco-habitat approach based on the principles of rezonation, revegetation, and revitalization (3R) [18].

Due to the intensive coal exploitation and deterioration of the environment in Shanxi Province in China, there has been a decrease in farmland. With the concept of "green mining industry", a basic method of reclamation in mining areas, an engineering study of mine reclamation, and a model of ecological agricultural reclamation in mining subsidence were developed. That study suggests implementing stereoscopic types of plantations, aquaculture and cropping and raising, as potential solutions [19]. Also, research into innovative technologies and the theory of land reclamation in the past 10 years included the analysis of exploitation, reclamation, land filling (Yellow River), self-reclamation, and topsoil alternative solutions in open-pit mines. In this research, which included the eastern, western, and southern zones, it was shown that several important laws and regulations were adopted for the five-year period. These important laws and regulations were successively promulgated, greatly promoting land reclamation [20].

Reclaimed mine soils developed at sites after coal mining form very diverse lithological layers that show significant variability depending on soil texture. However, a research study [21] showed that plant habitat is based on lithology and the genesis of sediments from parent rocks, so the predicted fertility potential of rock tailings resistant to weathering can be misinterpreted, providing an overestimated final result of habitat classification. Also, the implementation of a reclamation optimization plan is important for the construction of appropriate environmental protection projects and the regulation of life and production activities in the mining area during the completion of construction works [22].

Based on research in China [23], Concurrent Mining and Reclamation (CMR) technology was analyzed, and applied principles and technologies were provided for underground coal mining. That study showed that the advantages of a high percentage of land reclamation are adapted to the new technology. According to this research, CMR could increase the percentage of farmland reclamation to 37.59%, compared to the percentage of farmland reclamation post mining.

A study conducted in Loess, China, which investigated the regulation of soil nutrients, analyzed the degree of soil nutrients in different types of soil used. The study showed that nutrient levels in the soil increased significantly in the first five years after reclamation. In that study, four types of nutrients (potassium, phosphorus, nitrogen, and organic matter) in the soil were analyzed [24]. Based on the given levels of nutrients in the soil, guidelines were given for the precise management of reclaimed mining land with optimization measures of land reclamation. Also, some laboratory research on the physico-chemical parameters of soil substitutes showed the possibility of their application for the reclamation of highly acidic coal mine disposal sites. The results of applying soil cover to the used pits gave spontaneous successions of mesic and dry meadow species after the second year of vegetation growth. The content of heavy metals after the second year of vegetation showed a concentration of toxic metals (the share of which did not exceed the permitted level according to Polish standards), but it is possible to apply these reclaimed parts for green areas, wooded, and bushy lands [25].

Research based on linear programming techniques carried out in the area of the Banji mine in China, with an annual production of about three million tons of coal obtained from underground mining, showed that the reclamation carried out for the purpose of fishing, grain production, orchards, and the like was optimized under the limitation of fixed capital (capital, resources, workforce, etc.) [22].

Based on previous studies on mining soils [26–30], the specifics of soil properties that provide useful information for soil reclamation are particularly emphasized. The vulnerability of the mining area is caused by reclamation norms that have been studied but are difficult to apply in practice. Therefore, other comprehensive studies are also included, among others, research related to the application of the MCDM model [31–34]. Similar research has been proposed using the subjective–objective MCDM model in [31] in which AHP and Entropy were used to determine the criterion weights, while modified VIKOR sorted possible reclamation variants. However, this study considered only 3 possible variants, while we defined 11 alternatives in our study. Also, the methodology applied to calculate the significance of criteria requires quantitative data on the one hand, while, on the other, a large number of criteria need to be used, and all criteria should be considered simultaneously. Article [32] provided the MCDM framework for plant species for the reclamation of copper mines. While the methodologies of Fuzzy AHP, PROMETHEE (Preference Ranking Organization Method for Enrichment Evaluation), and Fuzzy TOPSIS (Technique for Order of Preference by Similarity to Ideal Solution) are old and have been extensively explored in prior studies, our research introduces a novel methodology to address the subject of research. The selection of a strategy for the sustainable transformation of a mine constitutes a complex decision-making process that presents various practical challenges [33]. Article [34] discusses the application of the strengths–weaknesses–opportunities–threats (SWOT) analysis and AHP for selecting a sustainable strategy, using the case study of a closed open-pit lignite mine in Greece.

A review of other studies suggests that we developed a highly comprehensive and appropriate tool for selecting a suitable sustainable reclamation variant for open-pit coal mining areas. The advantages of our proposed approach were discussed through research questions and partly in this section.

3. Research Methodology

3.1. Research Algorithm

Figure 1 presents a decision-making process algorithm for the selection of a reclamation solution for post-exploitation areas.

A universal methodology (the proposed IMF SWARA-Fuzzy ROV model), which is also applicable to open-pit mine reclamation, was applied. This paper tests and analyzes the Tamnava-West Field open-pit mine and disposal site in the Kolubara coal basin in Serbia. By analyzing the algorithm, the first step in starting activities in a mining company in terms of reclamation works is the initiation of a process for making a decision on the selection of a form of reclamation on a current post-exploitation terrain. After that, the collection of available data and bases for the analysis of possible reclamation solutions is started. Based on the availability of the required data, it is decided whether the documentation is sufficient or whether additional research, collection, processing, and updating are required. If sufficient input data, necessary documentation, and bases are available, the determination of applicable and technically and technologically feasible reclamation solutions is carried out. By applying MCDM based on the selection of the optimal method (IMF SWARA and Fuzzy ROV), the best (optimal) solution is selected, forming a ranking list of potential solutions. In this phase of the model, a tabular representation of possible, assumed variants or alternatives of reclamation solutions is provided. Based on the ranking, the selection of the final solution is made, thereby concluding the decision-making process.

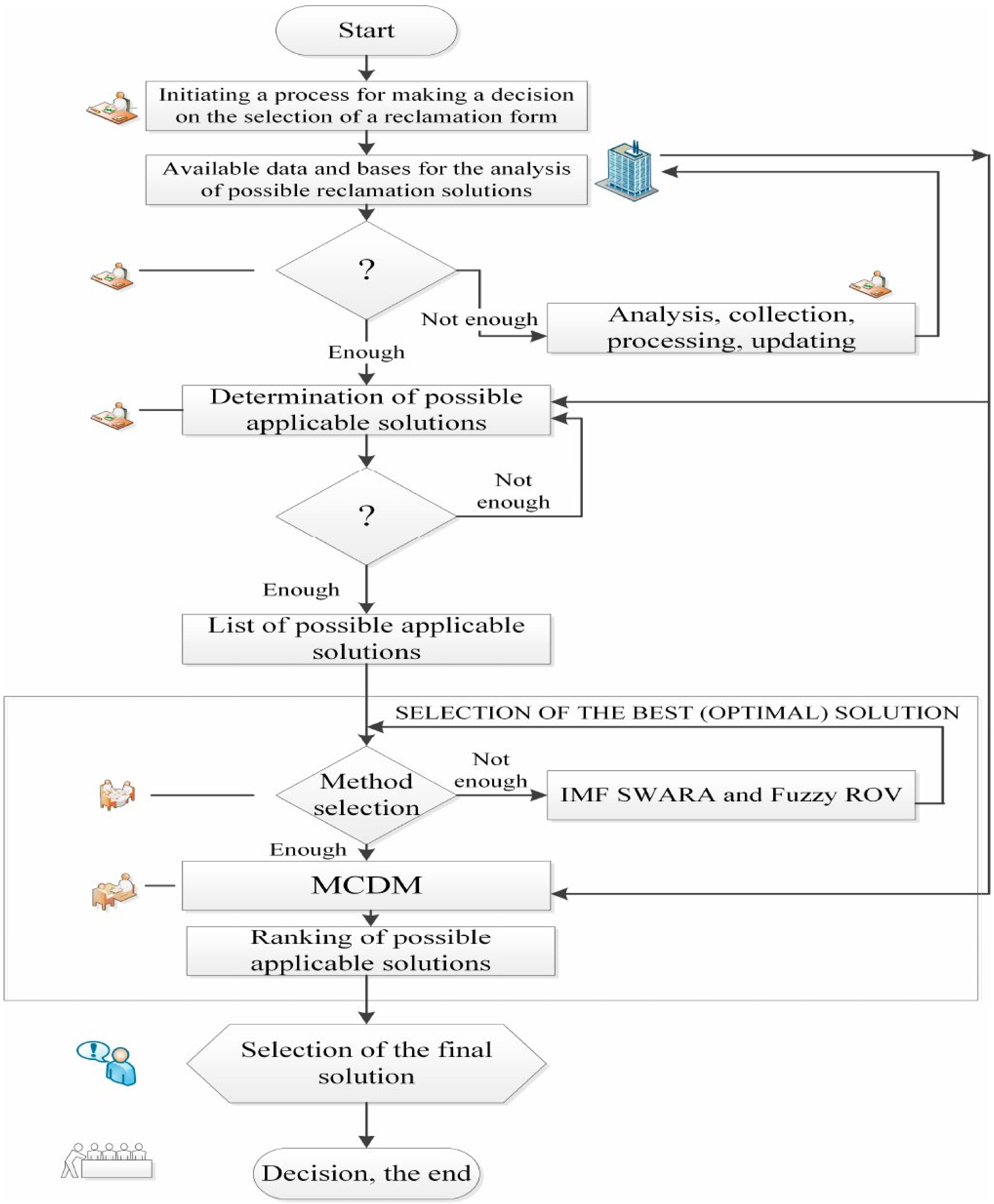

Figure 1. Algorithm of decision-making process in the selection of a reclamation solution.

3.2. IMF SWARA Method

The IMF SWARA method was created in study [35] and represents a method for calculating the values of criteria. The algorithm of this method is as follows [36,37]:

- Ranking of criteria from most important to least important.
  This step should determine how much criterion Cj is less important compared to $Cj - 1$, $\overline{\wp_j}$. according to the scale in Table 1.
- Determining the fuzzy coefficient $\overline{\Im_j}$ (1):

$$\overline{\Im_j} = \begin{cases} \overline{1} & j = 1 \\ \overline{\wp_j} \oplus \overline{1} & j > 1 \end{cases} \quad (1)$$

The comparative significance of the average value—$\overline{\wp_j}$.

- Determining the weights $\overline{\aleph_j}$ (2):

$$\overline{\aleph_j} = \begin{cases} \overline{1} & j = 1 \\ \frac{\overline{\aleph_{j-1}}}{\overline{\Im_j}} & j > 1 \end{cases} \quad (2)$$

where $\overline{\Im_j}$ is the fuzzy coefficient.

- Calculation of the fuzzy weight coefficients, Equation (3):

$$\overline{w_j} = \frac{\overline{\aleph_j}}{\sum_{j=1}^{n} \overline{\aleph_j}} \quad (3)$$

where $\overline{w_j}$ represents the fuzzy relative weight of the criteria j, and n the number of criteria.

Table 1. Linguistics and the Triangular Fuzzy Number (TFN) scale.

Linguistic Variable	Abbreviation	TFN Scale		
Absolutely less significant	ALS	1	1	1
Dominantly less significant	DLS	1/2	2/3	1
Much less significant	MLS	2/5	1/2	2/3
Really less significant	RLS	1/3	2/5	1/2
Less significant	LS	2/7	1/3	2/5
Moderately less significant	MDLS	1/4	2/7	1/3
Weakly less significant	WLS	2/9	1/4	2/7
Equally significant	ES	0	0	0

3.3. Fuzzy ROV Method

The Fuzzy ROV method was created by Ju et al. [38] and is represented through the following algorithm:

- Forming an MCDM model.
- Computation of fuzzy decision matrix $\aleph_{ij} = \left(\aleph_{ij}^{l}, \aleph_{ij}^{m}, \aleph_{ij}^{u}\right)_{n\times m}$.
- Normalization process, which is as follows. First, the elements $\Re_j$ and $\mathbb{R}_j$ should be defined:

$$\Re_j = \left(\Re_j^l, \Re_j^m, \Re_j^u\right) = \max(\aleph_{ij}) \quad (4)$$

$$\mathbb{R}_j = \left(\mathbb{R}_{j,}^l \mathbb{R}_{j,}^m \mathbb{R}_{j,}^u\right) = \min(\aleph_{ij}) \quad (5)$$

Next, it is necessary to calculate the difference between the values in the initial matrix and the min value κ_{ij}, and the difference between the max and min values of TFN, (ς_j):

$$\kappa_{ij} = \left(\kappa_{ij}^l, \kappa_{ij}^m, \kappa_{ij}^u\right) = \aleph_{ij} - \mathbb{R}_j = \left(\aleph_{ij}^l - \mathbb{R}_j^u, \aleph_{ij}^m - \mathbb{R}_j^m, \aleph_{ij}^u - \mathbb{R}_j^l\right) \quad (6)$$

$$\varsigma_j = \left(\varsigma_j^l, \varsigma_j^m, \varsigma_j^u\right) = \Re_j - \mathbb{R}_j = \left(\Re_j^l - \mathbb{R}_j^u, \Re_j^m - \mathbb{R}_j^m, \Re_j^u - \mathbb{R}_j^l\right) \quad (7)$$

The final normalized fuzzy values are as follows:

$$\vartheta_{ij} = \left(\vartheta_{ij}^l, \vartheta_{ij}^m, \vartheta_{ij}^u\right) = 1 + \left(\frac{\kappa_{ij}}{\varsigma_j}\right) = \left(\left(1 + \frac{\kappa_{ij}^l}{\varsigma_j^u}\right), \left(1 + \frac{\kappa_{ij}^m}{\varsigma_j^m}\right), \left(1 + \frac{\kappa_{ij}^u}{\varsigma_j^l}\right)\right) \quad (8)$$

In the final fuzzy normalized matrix, it may arise that the core concept of TFN is not satisfied, and it may be necessary to use Equation (9).

$$if\ \vartheta_{ij}^{m} \leq \vartheta_{ij}^{l}\ then\ \vartheta_{ij}^{m} = \vartheta_{ij}^{l},\ if\ \vartheta_{ij}^{u} \leq \vartheta_{ij}^{m}\ then\ \vartheta_{ij}^{u} = \vartheta_{ij}^{m} \tag{9}$$

Equations (6)–(8) are applied for benefit criteria, while, for the cost criteria, Equation (10) should be used:

$$\vartheta_{ij} = \left(\vartheta_{ij}^{l}, \vartheta_{ij}^{m}, \vartheta_{ij}^{u}\right) = 1 + \left(\frac{\mathbb{R}_j}{\aleph_{ij}}\right) = \left(\left(1 + \frac{\mathbb{R}_j^{l}}{\aleph_{ij}^{u}}\right), \left(1 + \frac{\mathbb{R}_j^{m}}{\aleph_{ij}^{m}}\right), \left(1 + \frac{\mathbb{R}_j^{u}}{\aleph_{ij}^{l}}\right)\right) \tag{10}$$

- Multiplication of the matrix ϑ_{ij} with the values of the factor w_j.

$$\nu_{ij} = \left(\nu_{ij}^{l}, \nu_{ij}^{m}, \nu_{ij}^{u}\right) = \vartheta_{ij} \otimes w_j = \left(\vartheta_{ij}^{l} \otimes w_j^{l}, \vartheta_{ij}^{m} \otimes w_j^{m}, \vartheta_{ij}^{u} \otimes w_j^{u}\right) \tag{11}$$

- Computation of the sum of the previous values depending on criteria types T_i^{+} (B) and T_i^{-} (C)

$$\mathrm{T}_i^{+} = \sum_{j=1}^{m}\left(\nu_{ij}^{+}\right) \tag{12}$$

$$\mathrm{T}_i^{-} = \sum_{j=1}^{m}\left(\nu_{ij}^{-}\right) \tag{13}$$

- Ranking alternatives from the highest to the lowest values according to results obtained using Equation (14):

$$\Lambda_i = \left(\frac{T_i^{+} + T_i^{-}}{2}\right) \tag{14}$$

4. Application of Criterion Analysis on the Mining Site

4.1. Description of Alternative Solutions and Evaluation Criteria

The selection of final reclamation solutions is made by teams of experts of various engineering profiles. The decision-making process algorithm in Figure 1 for selecting a reclamation solution can be used to gradually solve the problem of optimizing the management of reclamation processes in open-pit mines, so it is also applicable to the Tamnava-West Field coal mine in Figure 2. Figure 2a shows the Tamnava-West Field open-pit mine, where the deposition and transportation of excavated coal take place, while Figure 2b shows the machinery for coal mining in the mining basin.

(**a**) (**b**)

Figure 2. Display of the current state of the Tamnava-West Field open-pit mine.

Figure 3 shows a map of the mining basin with the locations of Tamnava-West Field and Tamnava-East Field, within which watercourses, roads, forests, fields, and meadows noticed in the mining fields are depicted.

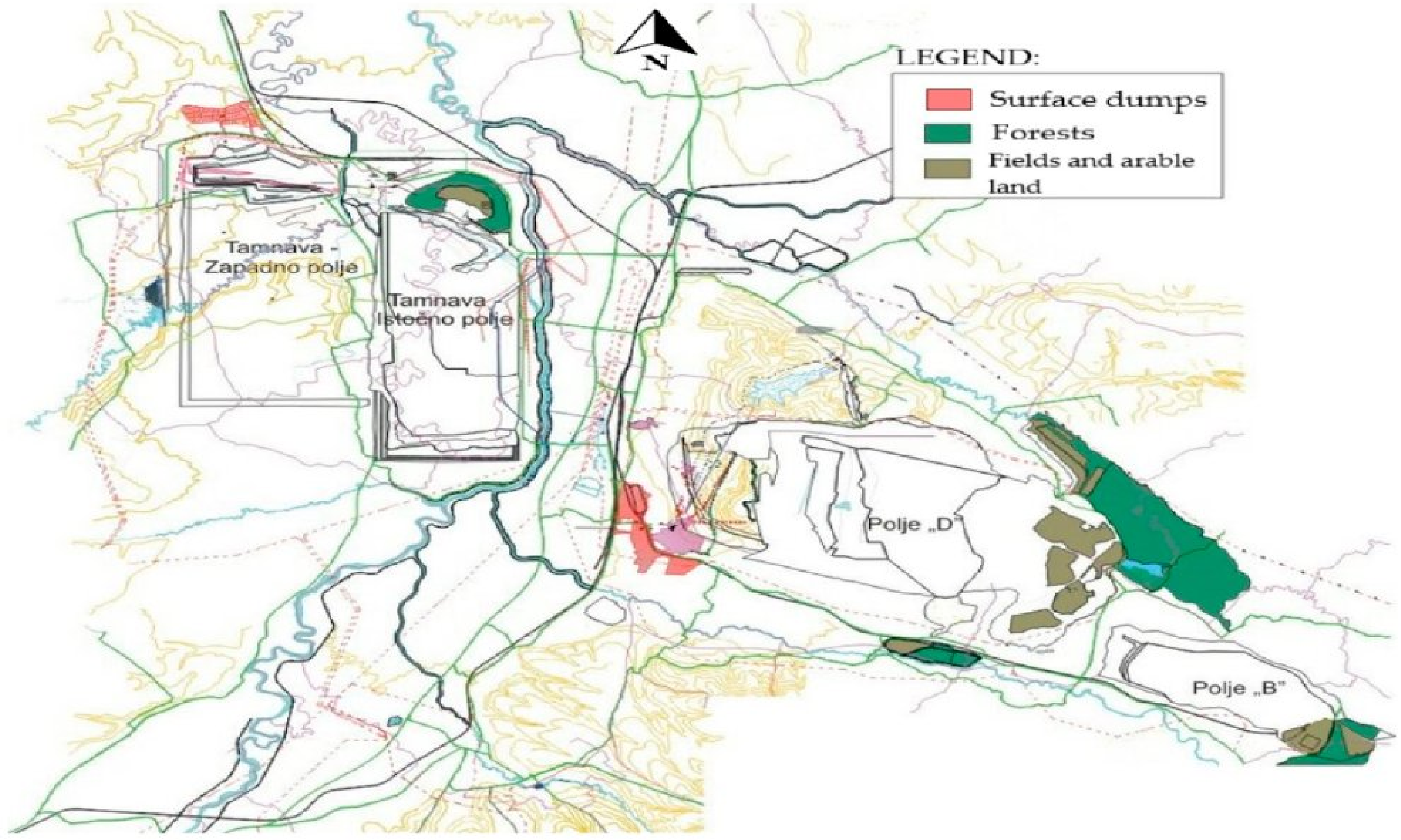

Figure 3. Location of Tamnava-West Field (Tamnava Zapadno polje) and Tamnava-East Field (Tamnava Istočno polje).

The process modeling of the unified reclamation system includes a total of 20 alternative variables (Table 2) of possible designed reclamation contents and the rehabilitation of the post-exploitation areas of open-pit mines and disposal sites: A1—Forestry; A2—Agriculture—growing crops and vegetables; A3—Agriculture—fruit growing; A4—Agriculture—viticulture, winemaking and cellaring; A5—Forestry and agriculture (combinations A1/A2–A4); A6—Aquatic complex (water areas) + fishery A6/A1–A5, A7; A7—Sports and recreation complex and in combination A7/A1–A6; A8—Park and horticultural arrangement (landscape architecture) A8/A6, A7; A9—Area for residential building and in combination A9/A8; A10—Zone for industrial construction; A11—Agricultural settlements and restitution for rural settlements + A11/A1–A6; A12—Museum-archaeological and cultural-historical area + A12/A1, A4, A8; A13—Tourist complex + A13/A1, A4, A6–A8, A12; A14—School and educational complex + A14/A1, A6–A8, A12; A15—Experimental and research centers (military and civilian) + A15/A5–A8, A14; A16—Temporary disposal sites (for ash, slag, tailings, municipal waste) + A16/A1, A10; A17—Spa and health complex + A17/A1, A4, A6–A8, A12, A13; A18—Livestock and farming complex + A18/A5–A8, A11, A13; A19—Expansion of nature reserves (biodiversity) + A19/A1, A4, A6–A8, A12, A13, A17, A18; A20—Leaving to spontaneous succession and self-reclamation.

In addition to the systematized possible solutions/variants, criteria for the selection of different types of reclamation solutions that represent appropriate sub-process systems of open-pit exploitation are also given. The selection of criteria covers the technical-technological, organizational, economic, social, and aesthetic aspects of evaluating the selected reclamation solutions, i.e., unified process activities.

As for the coal region, after reforestation, the expansion of nature reserves (biodiversity), a livestock and farming complex, and various types of agricultural (and fruit-growing) and forestry activities, water areas, and others are excellent forms of regeneration of this hilly–mountainous region. These solutions are logical considering the highest percentage share of these solutions on the one hand and their lower prices as investment interventions in terms of exploitation compared to competitive one-time and more expensive solutions on the other.

Table 2. Alternative variants for designing reclamation content.

Ord. Number	Variants or Alternatives of Reclamation Solutions
A1	Forestry
A2	Agriculture—growing crops and vegetables
A3	Agriculture—fruit growing
A4	Agriculture—viticulture, winemaking and cellaring
A5	Forestry and agriculture (combinations A1/A2–A4)
A6	Aquatic complex (water areas) + fishery A6/A1–A5, A7
A7	Sports and recreation complex and in combination A7/A1–A6
A8	Park and horticultural arrangement (landscape architecture) A8/A6, A7
A9	Area for residential building and in combination A9/A8
A10	Zone for industrial construction
A11	Agricultural settlements and restitution for rural settlements + A11/A1–A6
A12	Museum-archaeological and cultural-historical area + A12/A1, A4, A8
A13	Tourist complex + A13/A1, A4, A6–A8, A12
A14	School and educational complex + A14/A1, A6–A8, A12
A15	Experimental and research centers (military and civilian) + A15/A5–A8, A14
A16	Temporary disposal sites (for ash, slag, tailings, municipal waste) + A16/A1, A10
A17	Spa and health complex + A17/A1, A4, A6–A8, A12, A13
A18	Livestock and farming complex + A18/A5, A6–A8, A11, A13
A19	Expansion of nature reserves (biodiversity) + A19/A1, A4, A6–A8, A12, A13, A17, A18
A20	Leaving to spontaneous succession and self-reclamation

The categorization of criteria (Table 3) can be represented by numerical values, while, at the same time, some criteria are alternatively desirable, alternatively necessary, or without alternative either as deterministic or as descriptive data. By evaluating the criteria, first the limit values to which certain criteria aspire are defined, as minimum (min) and maximum (max). The selection of 12 criteria covers the technical-technological, organizational, economic, social, and aesthetic aspects of the evaluation of selected reclamation solutions, i.e., unified process activities.

A total of 20 potential reclamation variants were selected using a process approach, and, for the specific case of the Tamnava-West Field open-pit mine, 11 alternatives were defined and they mostly represent a combination of 2 or more alternatives. By selecting alternative reclamation solutions (Table 4) for degraded post-exploitation areas, it is necessary to fit into the previously defined spatial planning goals of mining basin areas. When determining the planned purposes of an area, the principles of concern for possible conflict between the economic or alternative use of the area and resources with the needs and goals of nature conservation are applied. In the event that the conflict cannot be resolved for priority purposes, additional research and development of a strategic environmental impact assessment and other complex analyses, which include both economic and social aspects, are carried out. The spatial plan confirms the legal obligation to reclaim areas where mineral raw materials, tailing areas, and municipal and industrial waste landfills are exploited, as well as the application of technical and biological environmental protection measures against the undesirable effects of these types of activities and facilities on the environment. Also, the need and the spatial framework are identified for afforestation, and anti-erosion protection facilities and measures (against water and aeolian erosion) are determined, primarily on open-pit mines, tailing areas, and ash pits. Tamnava-West Field is a vast lowland open-pit mine with horizontal and slightly inclined layers and interlayers of useful mineral raw material and interlayer tailings that requires the continuous technology of excavation and disposal, applying selective work.

Table 3. Criteria for the evaluation of reclamation alternatives for an open-pit coal mine.

Ord. No.	Criteria	Category	Evaluation (Min/Max)
C1	Amount of investments per unit area	Deterministic	Min
C2	Investment period—investment time	Deterministic	Max
C3	Time of return of invested funds	Deterministic	Min
C4	Annual costs of continuous maintenance per unit area	Deterministic	Min
C5	Adaptability of the reclamation solution into the ambient whole	Descriptive	Max
C6	Local needs (local community interest)	Descriptive	Max
C7	Technological complexity of carrying out reclamation works	Descriptive	Min
C8	Organizational demands (complexity) of the execution of works	Descriptive	Min
C9	Post-reclamation continuous maintenance time	Deterministic	Min
C10	The percentage share of the reclamation form (variant) in the total reclamation project	Deterministic	Max
C11	Social and economic importance of reclamation for the local community	Descriptive	Max
C12	Correlation between spatial and temporal dynamics of reclamation works	Descriptive	Max

Table 4. Potential reclamation solutions for the Tamnava-West Field open-pit mine.

A1	Forestry
A2	Agriculture (growing crops and vegetables)
A3	Forestry and agriculture (combination A1/A2)
A4	Aquatic complex (water areas) + fishery A6/A1–A5, A7
A5	Sports and recreation complex and in combination A7/A1–A6
A6	Zone for industrial construction
A7	Agricultural settlements and restitution for rural settlements + A11/A1–A6
A8	Temporary disposal sites (for ash, slag, tailings, etc.) + A16/A1, A10
A9	Livestock and farming complex + A18/A5–A8, A11, A13
A10	Expansion of nature reserves (biodiversity) + A19/A1, A4, A6–A8, A12, A13, A17, A18
A11	Leaving to spontaneous succession/self-reclamation

In addition, the following are given here as alternative solutions: A16—Temporary disposal sites (for ash, slag, tailings, etc.), which are created during exploitation according to the project; A7—Livestock and farming complex, as a possible solution in the post-exploitation period; A19—Expansion of nature reserves (biodiversity); A11—Agricultural settlements and restitution for rural settlements; and A10—Zone for industrial construction.

4.2. Calculation of Criterion Weights

When it comes to weights of criteria, which play a very important role in the evaluation of potential reclamation solutions, it is necessary to determine their values as objectively as possible. Accordingly, a total of five decision-makers were engaged to evaluate 12 criteria. The procedure implies that a total of five models of the IMF SWARA method, which represent the results for each DM individually, have been formed. Table 5 shows the results for the first decision-maker (DM).

Considering all five calculation models of the IMF SWARA method, it is necessary to perform averaging in order to obtain the final values that are later implemented in the Fuzzy ROV method. In this paper, the Bonferroni operator [39,40] is used to average the weights of five models of the IMF SWARA method and the final values are shown below.

$$w_1 = (0.089, 0.101, 0.118), w_2 = (0.071, 0.083, 0.100), w_3 = (0.065, 0.076, 0.092), w_4 = (0.114, 0.127, 0.145)$$
$$w_5 = (0.047, 0.058, 0.071), w_6 = (0.133, 0.143, 0.193), w_7 = (0.035, 0.045, 0.057), w_8 = (0.032, 0.041, 0.053)$$
$$w_9 = (0.065, 0.076, 0.092), w_{10} = (0.021, 0.029, 0.042), w_{11} = (0.141, 0.152, 0.171), w_{12} = (0.029, 0.037, 0.047)$$

The calculations obtained using the IMF SWARA method show that the social and economic importance of reclamation for the local community is the most significant criterion for decision-making in this research. Also, it should be noted that the next most important criterion is local needs, with a value almost equal to that of the most important criterion.

The least significant criterion is the correlation between spatial and temporal dynamics of reclamation works.

Table 5. Criterion weights for DM1 after applying the IMF SWARA algorithm.

Criteria	Criteria Comparison	Fuzzy Coefficient			Weights			Final Fuzzy Weight Coefficients		
	$\overline{\wp_j}$		$\overline{\Im_j}$			$\overline{\aleph_j}$			$\overline{w_j}$	
C6	WLS	1.000	1.000	1.000	1.000	1.000	1.000	0.179	0.193	0.212
C11	WLS	1.222	1.250	1.286	0.778	0.800	0.818	0.140	0.155	0.173
C4	MLS	1.222	1.250	1.286	0.605	0.640	0.669	0.109	0.124	0.142
C1	MLS	1.250	1.286	1.333	0.454	0.498	0.536	0.081	0.096	0.113
C2	ES	1.250	1.286	1.333	0.340	0.387	0.428	0.061	0.075	0.091
C3	ES	1.000	1.000	1.000	0.340	0.387	0.428	0.061	0.075	0.091
C9	MLS	1.000	1.000	1.000	0.340	0.387	0.428	0.061	0.075	0.091
C5	LS	1.250	1.286	1.333	0.255	0.301	0.343	0.046	0.058	0.073
C7	ES	1.286	1.333	1.400	0.182	0.226	0.267	0.033	0.044	0.056
C8	WLS	1.000	1.000	1.000	0.182	0.226	0.267	0.033	0.044	0.056
C12	LS	1.222	1.250	1.286	0.142	0.181	0.218	0.025	0.035	0.046
C10	WLS	1.286	1.333	1.400	0.101	0.136	0.170	0.018	0.026	0.036
				SUM	4.720	5.168	5.572			

4.3. Ranking of Alternative Solutions with the Fuzzy ROV Method

After calculating the weights of the criteria, the model is calculated with the Fuzzy ROV method. First, a linguistic evaluation of the reclamation solutions is performed, which is shown in Table 6.

Table 6. Initial linguistic matrix.

	C1	C2	C3	C4	C5	C6	C7	C8	C9	C10	C11	C12
A1	VG	EG	EG	EG	EG	MG	G	G	P	VG	EG	G
A2	MP	EP	VP	M	EG	VG	M	M	P	VG	EG	M
A3	MP	G	MG	G	EG	G	MG	MG	P	EG	EG	MG
A4	VG	EP	EG	EG	G	MP	EG	EG	P	VP	M	VP
A5	MP	MG	EG	VP	G	EG	MP	MP	VP	P	G	VP
A6	EP	VP	EG	VP	G	EG	MG	VG	VG	M	EG	G
A7	P	EG	MG	VP	EG	EG	G	MP	P	M	EG	VP
A8	MP	EP	VP	EG	G	M	EG	EG	VG	EP	M	EG
A9	P	EG	EG	VP	EG	EG	MP	MG	VP	VP	VG	VP
A10	EG	VG	MG	MG	EG	P	MG	VG	MG	P	M	M
A11	EG	EP	MG	EG	M	MG	EG	EG	VG	MP	VP	MG

EP—extremely poor; VP—very poor; P—poor; MP—medium poor; M—medium; MG—medium good; G—good; VG—very good; EG—extremely good.

After that, the linguistic values are transformed into TFNs, which are shown in Table 7. This transformation is performed on the basis of the scale shown in study [41]. The initial TFN decision matrix in the Fuzzy ROV method is shown below.

It should be emphasized that all criteria were modeled as benefit, i.e., the extreme values were identified as desirable and the best grades were assigned. Applying the Fuzzy ROV method algorithm shown above, the results presented in Table 8 were obtained.

The results obtained using the hybrid IMF SWARA—Fuzzy ROV model show that the first reclamation alternative representing forestry is the best for the Tamnava-West Field open-pit mine. A3—Forestry and agriculture (combination A1/A2) appears as the second-ranked alternative, while the worst reclamation alternative according to the defined fuzzy MCDM model is A5—Sports and recreation complex and in combination A7/A1–A6.

Table 7. Initial Fuzzy ROV matrix.

	C1	C2	C3	C4	C5	C6	C7	C8	C9	C10	C11	C12
A1	(7,7,9)	(7,9,9)	(7,9,9)	(7,9,9)	(7,9,9)	(5,5,7)	(5,7,7)	(5,7,7)	(1,3,3)	(7,7,9)	(7,9,9)	(5,7,7)
A2	(3,3,5)	(1,1,1)	(1,1,3)	(3,5,5)	(7,9,9)	(7,7,9)	(3,5,5)	(3,5,5)	(1,3,3)	(7,7,9)	(7,9,9)	(3,5,5)
A3	(3,3,5)	(5,7,7)	(5,5,7)	(5,7,7)	(7,9,9)	(5,7,7)	(5,5,7)	(5,5,7)	(1,3,3)	(7,9,9)	(7,9,9)	(5,5,7)
A4	(7,7,9)	(1,1,1)	(7,9,9)	(7,9,9)	(5,7,7)	(3,3,5)	(7,9,9)	(7,9,9)	(1,3,3)	(1,1,3)	(3,5,5)	(1,1,3)
A5	(3,3,5)	(5,5,7)	(7,9,9)	(1,1,3)	(5,7,7)	(7,9,9)	(3,3,5)	(3,3,5)	(1,1,3)	(1,3,3)	(5,7,7)	(1,1,3)
A6	(1,1,1)	(1,1,3)	(7,9,9)	(1,1,3)	(5,7,7)	(7,9,9)	(5,5,7)	(7,7,9)	(7,7,9)	(3,5,5)	(7,9,9)	(5,7,7)
A7	(1,3,3)	(7,9,9)	(5,5,7)	(1,1,3)	(7,9,9)	(7,9,9)	(5,7,7)	(3,3,5)	(1,3,3)	(3,5,5)	(7,9,9)	(1,1,3)
A8	(3,5,5)	(1,1,1)	(1,1,3)	(7,9,9)	(5,7,7)	(3,5,5)	(7,9,9)	(7,9,9)	(7,7,9)	(1,1,1)	(3,5,5)	(7,9,9)
A9	(1,3,3)	(7,9,9)	(7,9,9)	(1,1,3)	(7,9,9)	(7,9,9)	(3,3,5)	(5,5,7)	(1,1,3)	(1,1,3)	(7,7,9)	(1,1,3)
A10	(7,9,9)	(7,7,9)	(5,5,7)	(5,5,7)	(7,9,9)	(1,3,3)	(5,5,7)	(7,7,9)	(5,5,7)	(1,3,3)	(3,5,5)	(3,5,5)
A11	(7,9,9)	(1,1,1)	(5,5,7)	(7,9,9)	(3,5,5)	(5,5,7)	(7,9,9)	(7,9,9)	(7,7,9)	(3,3,5)	(1,1,3)	(5,5,7)

Table 8. Results of the hybrid IMF SWARA—Fuzzy ROV model.

	Sum of Weighted Elements for Benefit Criteria T_i^+			DF	Alternatives	Sorting
A1	1.176	1.720	3.189	1.874	Forestry	1
A2	0.976	1.456	2.657	1.576	Agriculture (growing crops and vegetables)	10
A3	1.069	1.596	2.958	1.735	Forestry and agriculture (combination A1/A2)	2
A4	0.995	1.463	2.737	1.597	Aquatic complex (water areas) + fishery A6/A1–A5, A7	9
A5	0.958	1.404	2.599	1.529	Sports and recreation complex and in combination A7/A1–A6	11
A6	1.036	1.529	2.902	1.676	Zone for industrial construction	3
A7	1.005	1.537	2.775	1.655	Agricultural settlements and restitution for rural settlements + A11/A1–A6	4
A8	0.972	1.497	2.715	1.612	Temporary disposal sites (for ash, slag, tailings, etc.) + A16/A1, A10	8
A9	1.015	1.481	2.803	1.624	Livestock and farming complex + A18/A5–A8, A11, A13	5
A10	1.014	1.486	2.785	1.624	Expansion of nature reserves (biodiversity) + A19/A1, A4, A6–A8, A12, A13, A17, A18	6
A11	1.029	1.469	2.830	1.623	Leaving to spontaneous succession/self-reclamation	7

5. Verification Tests and Discussion

This part of the study is dedicated to the three-phase verification procedure of the initially obtained solutions, and includes the simulation of new criterion weights, comparative MCDM analysis, and the calculation of statistical correlation tests.

5.1. Changing the Weights of the Criteria (Sensitivity Analysis)

In each MCDM model, criteria play an important role, and by simulating their weights through new scenarios, it is possible to identify a potential change in the ranks of alternatives [42,43], i.e., in this case, reclamation solutions. Thus, it is possible to include all potential results and their changes and strive towards their proactive management. In this part, 12 × 10 = 120 scenarios were formed, in which the weights of all 12 criteria were modeled in the 5–95% interval. The values of the new weights across the scenarios are given in Figure 4.

In the initial scenario, which includes criterion weights obtained with the IMF SWARA method, the lowest value is for the tenth criterion (0.021, 0.029, 0.042), and the highest is for the sixth criterion (0.133, 0.143, 0.193). In the hundredth scenario, the tenth criterion has the lowest value (0.001, 0.001, 0.002), which means that it tends to zero and that the value of this criterion is reduced to negligible importance. On the other hand, an extreme value is in the 110th scenario for the sixth criterion (0.153, 0.167, 0.231). It is important to note here that, in this scenario, the minimum value is of the second most significant criterion, and that is C11.

Figure 5 shows the new ranks of the reclamation variants in accordance with the previously simulated new weights of the criteria and their mutual relationship.

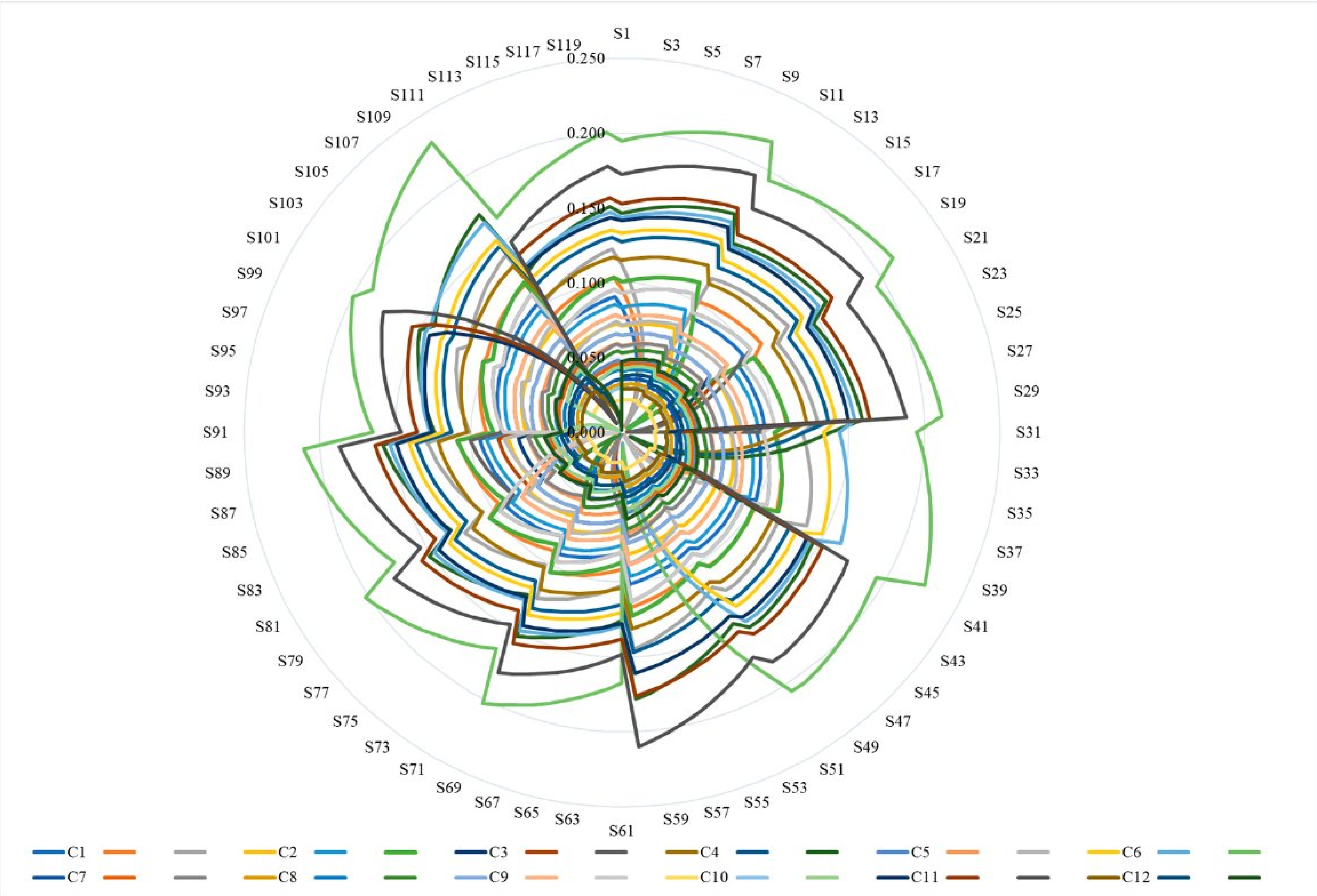

Figure 4. Simulated weights of criteria for the evaluation of reclamation variants for the open-pit mine through 120 scenarios.

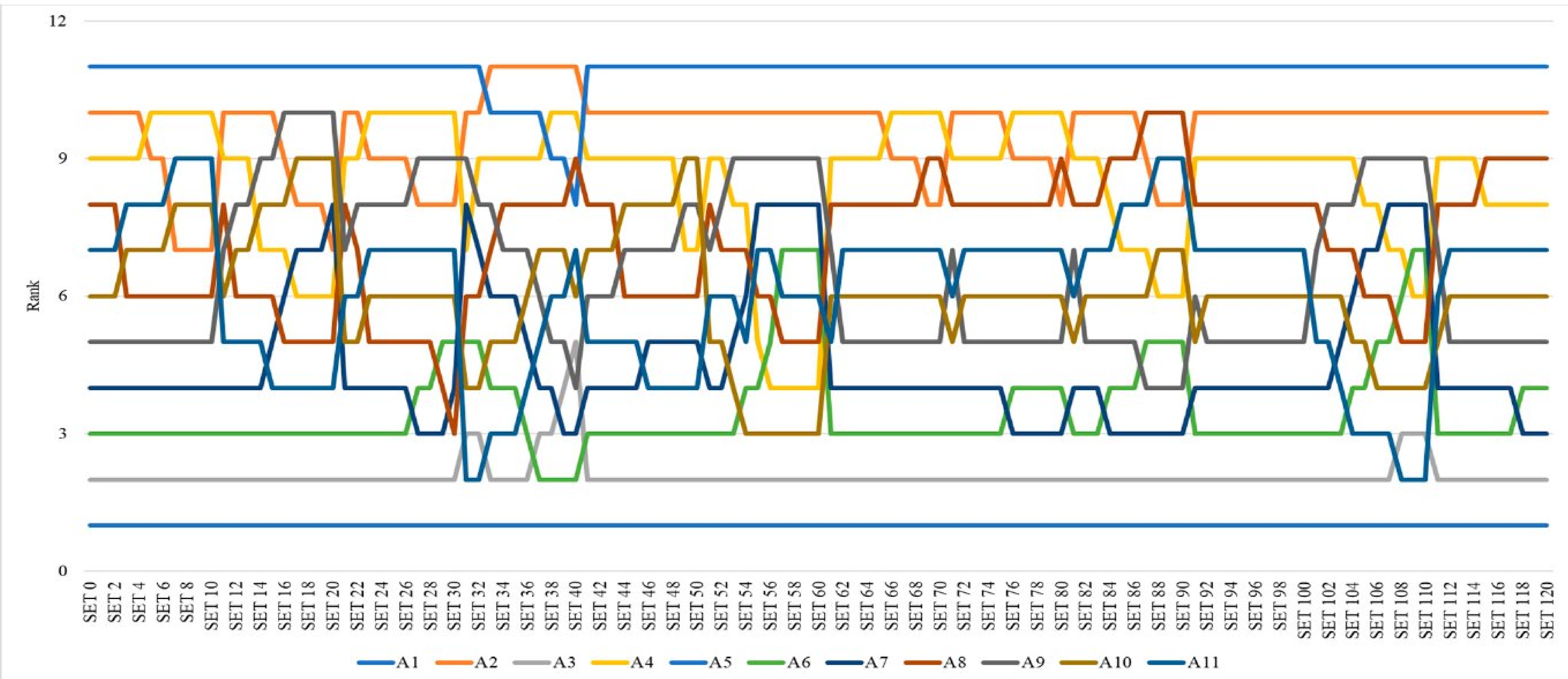

Figure 5. New ranks of reclamation variants for the open-pit mine defined in SA.

The results of the sensitivity analysis (Figure 5) show a great influence of changes in weighting coefficients, that is, the sensitivity of initial results in relation to changes in the values of the criteria. The only reclamation alternative, which is ultimately the most important, is A1—Forestry, which remains in first place regardless of the value of any criterion. Other alternatives change their positions by even several places depending on a scenario. The greatest deviation is for A5 (1.789), which, in certain scenarios, changes its position even by five places, and this is a consequence of reducing the importance of the second and eighth criteria. It is important to emphasize that the standard deviation (in addition to the first alternative that does not change) is the least for the second best reclamation alternative (A3 = 0.396) and for the last-ranked alternative (A5 = 0.416). Other reclamation alternatives change their ranks in most scenarios depending on their performance according to the best criterion.

5.2. Comparative Analysis

The results obtained with IMF SWARA—Fuzzy ROV were compared with three other fuzzy MCDM methods, F-MARCOS [41], F-SAW [44], and F-WASPAS [45], as shown in Figure 6.

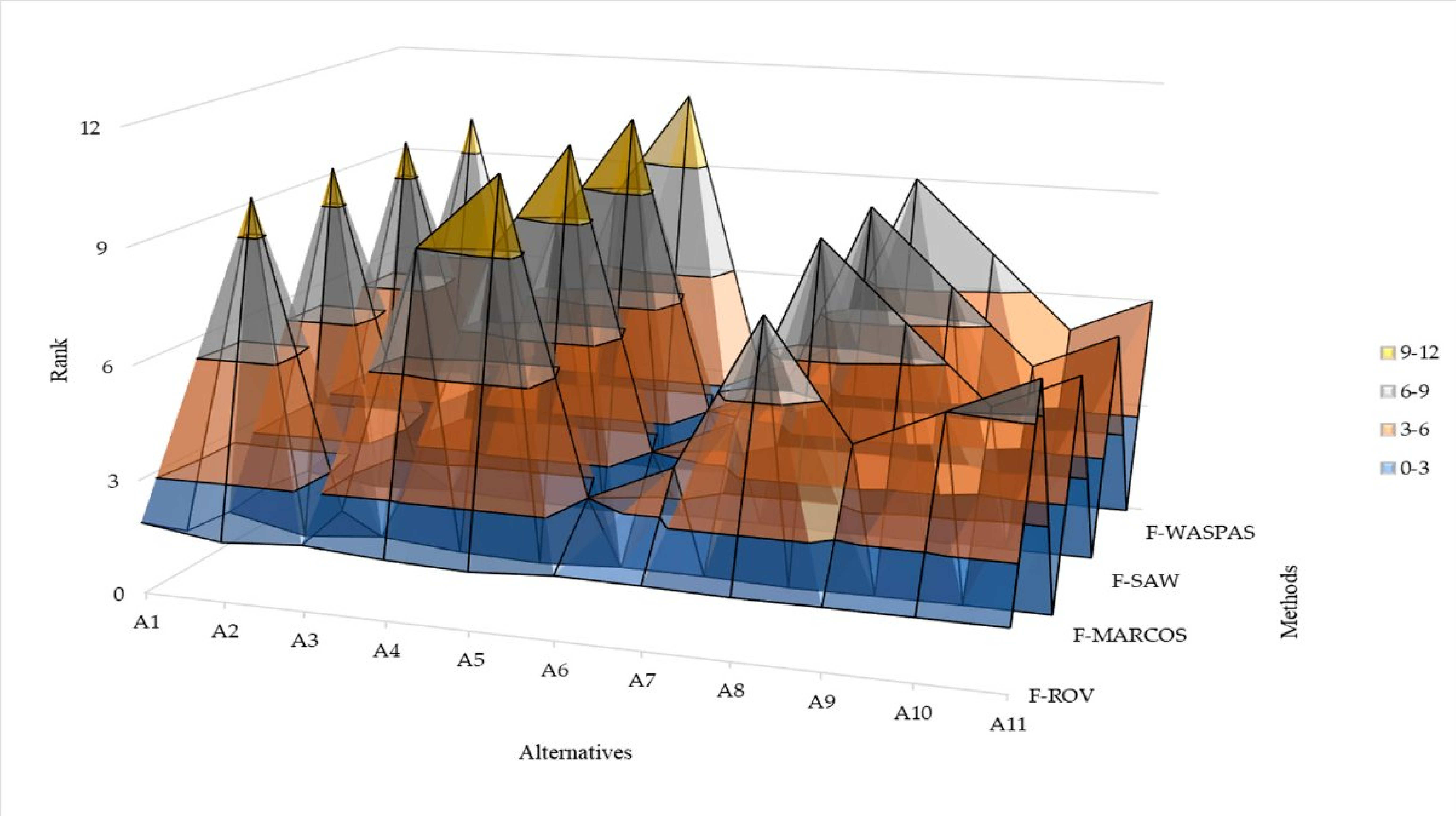

Figure 6. Ranking of alternatives using four different fuzzy MCDM methods.

The results obtained after comparison with three fuzzy MCDM methods show that there are certain minor deviations that are primarily related to the reclamation solutions that are ranked lower. Five out of eleven alternatives in total show changes in positions by only one or two places. For example: A4 is ranked fourth with Fuzzy ROV, while according to other methods, it is placed eighth. The remaining changes are as follows: A8 ($8 \rightarrow 9$), A9 ($5 \rightarrow 7$), A10 ($6 \rightarrow 5$), and A11 ($7 \rightarrow 6$). This confirms the initial results obtained with the IMF SWARA—Fuzzy ROV model.

5.3. Calculation of Correlation for Newly Obtained Ranks in Verification Tests

Since it was identified that there are deviations in the sensitivity analysis and small deviations in the comparative analysis, the statistical correlation of all ranks was calculated, as shown in Figure 7. The calculated correlation refers to the WS [46] and SSC [47] coefficients.

As previously determined and noted in the sensitivity analysis, the model is sensitive to changes in the weights of the criteria, so some reclamation solutions have fallen by even five positions. In general, the average values are extremely high, SCC = 0.901 and WS = 0.966, considering that there are as many as 120 formed scenarios. The lowest statistical correlation is SCC = 0.564, WS = 0.838 in scenario 110, as previously explained. Of course, in a certain number of scenarios, there is a total correlation of the results.

Figure 8 shows the calculated correlation values for the comparative analysis.

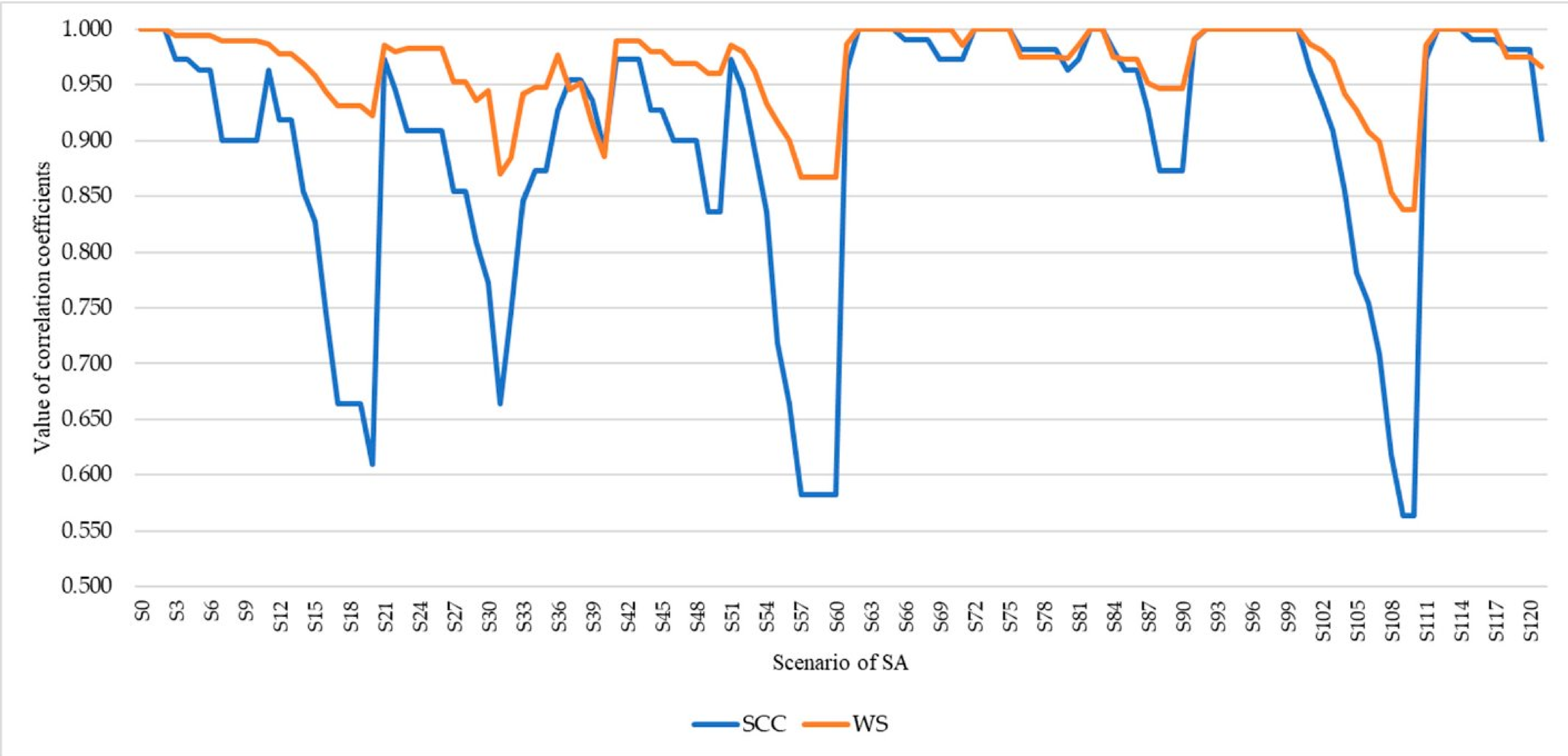

Figure 7. Correlation of results in SA.

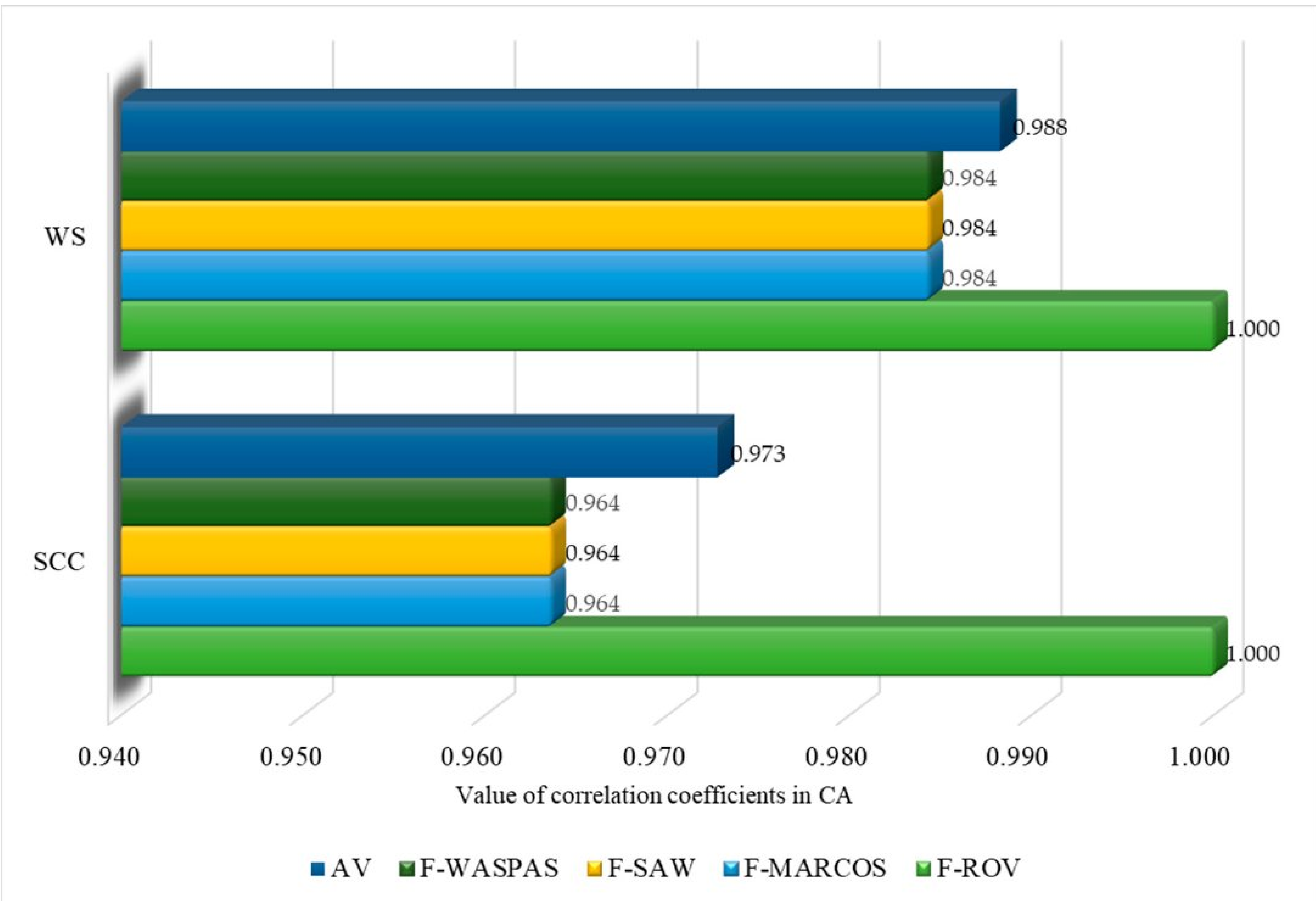

Figure 8. Correlation of IMF SWARA—Fuzzy ROV with other methods.

Since there are relatively small deviations in the ranks of reclamation solutions, statistical correlation tests tend towards a total correlation, i.e., a value of 1.00. The average correlations are SCC = 0.973 and WS = 0.988, and Fuzzy ROV has a correlation with other methods of 0.964 and 0.984, respectively.

6. Conclusions

The issue of environmental protection and an adequate approach to achieving sustainable development is a priority in all areas of action. In this paper, the problem of reclamation of an open-pit mining area after its exploitation is considered. A total of 20 potential reclamation variants were selected using a process approach, and for the specific case of the Tamnava-West Field open-pit mine, 11 alternatives were defined and they mostly represent a combination of 2 or more alternatives. For the purpose of evaluating these reclamation variants, a total of 12 criteria were defined and a hybrid IMF SWARA—Fuzzy ROV model was created for the first time in the literature; this model is applicable in all areas of decision-making and evaluation of variant solutions. The results show that the reclamation variant related to forestry is optimal under the considered conditions of multi-criteria evaluation. This is confirmed through verification systems. In accordance with the potential of the considered open-pit mine, it is necessary to apply the selected solution and start its implementation.

The benefits of the conducted research can be viewed through the prism of engineering and social and mathematical aspects. Advantages include considering almost all possible variants for the reclamation of open-pit coal mining areas, and their integration for specific cases, defining all sustainable inputs for their evaluation, and finally developing a proper integrated mathematical tool for precisely determining criterion weights and sorting alternatives. The selection of the right and most suitable sustainable solution for the reclamation of open-pit coal mining areas is one of the key social and environmental tasks. Thus, this study can contribute to achieving sustainable development goals. The limitations of this study can be manifested by the fact that it only considers coal mining, and the number of experts included in the evaluation process could also be larger.

Future research is related to the consideration of other open-pit mines, their evaluation, and the selection of an optimal variant, certainly depending on the specific characteristics of those mines. Additionally, the development and application of new models in the theory of uncertainty can constitute future tasks.

Author Contributions: Conceptualization, B.D. and T.Š.; methodology, Ž.S. and M.S; validation, M.K. and F.A.; formal analysis, B.D.; investigation, B.D.; data curation, B.D. and T.Š; writing—original draft preparation, B.D. and Ž.S.; writing—review and editing, M.S., M.K., and F.A; visualization, M.K.; supervision, T.Š.; funding acquisition, M.K. and F.A. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: The raw data supporting the conclusions of this article will be made available by the authors on request.

Acknowledgments: The authors are thankful to the deanship of Graduate Studies and Scientific Research at University of Bisha for supporting this work through the fast-track research support program. Authors B.D. and T.Š. express their gratitude to the Ministry of Education, Science and Technological Development of the Republic of Serbia for supporting the scientific research, which is essential for the advancement of a knowledge-based society.

Conflicts of Interest: The authors declare no conflicts of interest.

References

1. Kasztelewicz, Z. Approaches to Post-Mining Land Reclamation in Polish Open-Cast Lignite Mining. *Civ. Environ. Eng. Rep.* **2014**, *12*, 55–67. [CrossRef]
2. Spasić, M.; Borůvka, L.; Vacek, O.; Drábek, O.; Tejnecký, V. Pedogenesis problems on reclaimed coal mining sites. *Soil Water Res.* **2021**, *16*, 137–150. [CrossRef]
3. Harley, A.G.; Wexner, H. *The Struggle for Sustainable Development in Appalachia's Mineral Rich Mountains*; M-RCBG Associate Working Paper Series | No. 184; Harvard University: Cambridge, MA, USA, 2022.

4. Guidance on How to Provide Evidence in Support of a Request for the Welsh Ministers' Approval of a Coal Authority Mining Operation Licence. Requesting Approval for Coal Authority Mining Operation Licences, Welsh Government Services and Information. 2022. Available online: https://www.gov.wales/requesting-approval-coal-authority-mining-operation-licences-html-0 (accessed on 3 January 2024).
5. Panagopoulos, I.; Karayannis, A.; Adam, K.; Aravossis, K. Project and Risk Management for the Reclamation of Old Mine Sites. In Proceedings of the International Conference of Environmental Management, Engineering, Planning and Economics, Skiathos Island, Greece, 24–28 June 2007; pp. 667–673.
6. Panagopoulos, I.; Karayannis, A.; Adam, K.; Aravossis, K. Application of risk management techniques for the remediation of an old mining site in Greece. *Waste Manag.* **2009**, *29*, 1739–1746. [CrossRef]
7. Krzaklewski, W.; Pietrzykowski, M. Site classification in post-mining areas reclaimed for forest use with special focus on phytosociological-soil metho. *Sylwan* **2007**, *151*, 51–57.
8. Pietrzykowski, M.; Krzaklewski, W. Reclamation–interaction of technology and ecology. In *Monograph: Lignite—The Chances and the Treaths*; Sierpień, D., Ed.; Academy of Mining and Metallurgy AGH: Krakow, Poland, 2014; pp. 333–343.
9. Spasić, M.; Drábek, O.; Borůvka, L.; Tejnecký, V. Trends of Global Scientific Research on Reclaimed Coal Mine Sites between 2015 and 2020. *Appl. Sci.* **2023**, *13*, 8412. [CrossRef]
10. Frauenstein, J. Lignite mining and rehabilitation. In Proceedings of the Common Forumm Meeting, Helsinki, Finland, 8 December 2009.
11. Sloss, L. Coal Mine Site Reclamation CCC/216. International Energy Association Clean Coal Centre. 2013. Available online: https://www.usea.org/sites/default/files/022013_Coal%20mine%20site%20reclamation_ccc216.pdf (accessed on 3 April 2024).
12. Zhang, R.; Chugh, Y.P. Sustainable Development of Underground Coal Resources in Shallow Groundwater Areas for Environment and Socio-Economic Considerations: A Case Study of Zhangji Coal Mine in China. *Int. J. Environ. Res. Public Health* **2023**, *20*, 5213. [CrossRef] [PubMed]
13. Li, Z.; Wu, S.; Zhang, S.; Nie, C.; Li, Y.; Huang, Y. Optimization of Land Reuse Structure in Coal Mining Subsided Areas Considering Regional Economic Development: A Case Study in Pei County, China. *Sustainability* **2020**, *12*, 3335. [CrossRef]
14. Kaźmierczak, U.; Strzałkowski, P.; Lorenc, M.W.; Szumska, E.; Sánchez, A.A.P.; Baker, K.A.C. Post-mining Remnants and Revitalization. *Geoheritage* **2019**, *11*, 2025–2044. [CrossRef]
15. Więckol-Ryk, A.; Pierzchała, Ł.; Bauerek, A.; Krzemie'n, A. Minimising Coal Mining's Impact on Biodiversity: Artificial Soils for Post-Mining Land Reclamation. *Sustainability* **2023**, *15*, 9707. [CrossRef]
16. Baidowi, N.; Rosyidi, C.N.; Aisyati, A. A Cut-Off Grade Optimization Model in Open Pit Mining Considering Reclamation Cost and Revenue. *IOP Conf. Ser. Mater. Sci. Eng.* **2021**, *1096*, 012021. [CrossRef]
17. Craynon, J.; Karmis, M. Integrating sustainability in coal mining operations. In Proceedings of the 3rd International Conference on Sustainable Development Indicators in the Minerals Industry, Milos Island, Greece, 17–20 June 2007.
18. Pambudi, P.A.; Utomo, S.W.; Soelarno, S.W.; Takarina, N.D. Coal mining reclamation as an environmental recovery effort: A review. *J. Degrad. Min. Lands Manag.* **2023**, *10*, 4811–4821. [CrossRef]
19. Hao, B.-y.; Kang, L.-x. Mine Land Reclamation and Eco-Reconstruction in Shanxi Province I: Mine Land Reclamation Model. *Sci. World J.* **2014**, *2014*, 483862. [CrossRef] [PubMed]
20. Xiao, W.; Hu, Z.; Fu, Y. Zoning of land reclamation in coal mining area and new progresses for the past 10 years. *Int. J. Coal Sci. Technol.* **2014**, *1*, 177–183. [CrossRef]
21. Pietrzykowski, M.; Krzaklewski, W. Reclamation of Mine Lands in Poland. In *Bio-Geotechnologies for Mine Site Rehabilitation*; Elsevier: Amsterdam, The Netherlands, 2018; pp. 493–513. [CrossRef]
22. Xu, L.; Song, H.; Jin, W. Optimizing the Structures of Reclaimed Land Use in Coal Mining Area. In Proceedings of the 2009 3rd International Conference on Bioinformatics and Biomedical Engineering, Beijing, China, 11–13 June 2009. [CrossRef]
23. Hu, Z.; Xiao, W.; Fu, Y. Introduction to Concurrent Mining and Reclamation for Coal Mines in China. In *Mine Planning and Equipment Selection*; Drebenstedt, C., Singhal, R., Eds.; Springer: Cham, Switzerland, 2014. [CrossRef]
24. Fan, X.; Guan, Y.; Bai, Z.; Zhou, W.; Zhu, C. Optimization of Reclamation Measures in a Mining Area by Analysis of Variations in Soil Nutrient Grades under Different Types of Land Usage—A Case Study of Pingshuo Coal Mine, China. *Land* **2022**, *11*, 321. [CrossRef]
25. Vangronsveld, J.; Van Assche, F.; Clijsters, H. Reclamation of a bare industrial area contaminated by non-ferrous metals: In situ metal immobilization and revegetation. *Environ. Pollut.* **1995**, *87*, 51–59. [CrossRef]
26. Bao, N.; Wu, L.; Ye, B.; Yang, K.; Zhou, W. Assessing soil organic matter of reclaimed soil from a large surface coal mine using a field spectroradiometer in laboratory. *Geoderma* **2017**, *288*, 47–55. [CrossRef]
27. Liu, X.; Bai, Z.; Zhou, W.; Cao, Y.; Zhang, G. Changes in soil properties in the soil profile after mining and reclamation in an opencast coal mine on the Loess Plateau, China. *Ecol. Eng.* **2017**, *98*, 228–239. [CrossRef]
28. Mukhopadhyay, S.; Masto, R.E.; Yadav, A.; George, J.; Ram, L.C.; Shukla, S.P. Soil quality index for evaluation of reclaimed coal mine spoil. *Sci. Total Environ.* **2016**, *542*, 540–550. [CrossRef] [PubMed]
29. Noviyanto, A.; Purwanto, P.; Minardi, S.; Supriyadi, S. The assessment of soil quality of various age of land reclamation after coal mining: A chronosequence study. *J. Degrade. Min. Land Manag.* **2017**, *5*, 1009–1018. [CrossRef]

30. Domínguez-Haydar, Y.; Velásquez, E.; Carmona, J.; Lavelle, P.; Chavez, L.F.; Jiménez, J.J. Evaluation of reclamation success in an open-pit coal mine using integrated soil physical, chemical and biological quality indicators. *Ecol. Indic.* **2019**, *103*, 182–193. [CrossRef]
31. Zhou, W.; Yin, W.; Peng, X.; Liu, F.; Yang, F. Comprehensive evaluation of land reclamation and utilisation schemes based on a modified VIKOR method for surface mines. *Int. J. Min. Reclam. Environ.* **2018**, *32*, 93–108. [CrossRef]
32. Ebrahimabadi, A.; Pouresmaieli, M.; Afradi, A.; Pouresmaeili, E.; Nouri, S. Comparing two methods of PROMETHEE and Fuzzy TOPSIS in selecting the best plant species for the reclamation of Sarcheshmeh copper mine. *Asian J. Water Environ. Pollut.* **2018**, *15*, 141–152. [CrossRef]
33. Spanidis, P.M.; Roumpos, C.; Pavloudakis, F. Evaluation of Strategies for the Sustainable Transformation of Surface Coal Mines Using a Combined SWOT–AHP Methodology. *Sustainability* **2023**, *15*, 7785. [CrossRef]
34. Rakhmangulov, A.; Burmistrov, K.; Osintsev, N. Selection of open-pit mining and technical system's sustainable development strategies based on MCDM. *Sustainability* **2022**, *14*, 8003. [CrossRef]
35. Vrtagić, S.; Softić, E.; Subotić, M.; Stević, Ž.; Dordevic, M.; Ponjavic, M. Ranking road sections based on MCDM model: New improved fuzzy SWARA (IMF SWARA). *Axioms* **2021**, *10*, 92. [CrossRef]
36. Badi, I.; Bouraima, M.B. Development of MCDM-based Frameworks for Proactively Managing the Most Critical Risk Factors for Transport Accidents: A Case Study in Libya. *Spectr. Eng. Manag. Sci.* **2023**, *1*, 38–47. [CrossRef]
37. Damjanović, M.; Stević, Ž.; Stanimirović, D.; Tanackov, I.; Marinković, D. Impact of the number of vehicles on traffic safety: Multiphase modeling. *Facta Univ. Ser. Mech. Eng.* **2022**, *20*, 177–197. [CrossRef]
38. Ju, M.; Mirović, I.; Petrović, V.; Erceg, Ž.; Stević, Ž. A Novel Approach for the Assessment of Logistics Performance Index of EU Countries. *Economics* **2024**, *18*, 20220074. [CrossRef]
39. Radovanović, M.; Božanić, D.; Tešić, D.; Puška, A.; Hezam, I.M.; Jana, C. Application of hybrid DIBR-FUCOM-LMAW-Bonferroni-grey-EDAS model in multicriteria decision-making. *Facta Univ. Ser. Mech. Eng.* **2023**, *21*, 387–403. [CrossRef]
40. Tešić, D.; Božanić, D.; Radovanović, M.; Petrovski, A. Optimising Assault Boat Selection for Military Operations: An Application of the DIBR II-BM-CoCoSo MCDM Model. *J. Intell. Manag. Decis.* **2023**, *2*, 160–171. [CrossRef]
41. Stanković, M.; Stević, Ž.; Das, D.K.; Subotić, M.; Pamučar, D. A new fuzzy MARCOS method for road traffic risk analysis. *Mathematics* **2020**, *8*, 457. [CrossRef]
42. Puška, A.; Hodžić, I.; Štilić, A.; Murtič, S. Evaluating European Union Countries on Climate Change Management: A Fuzzy MABAC Approach to the Climate Change Performance Index. *J. Green Econ. Low-Carbon Dev.* **2024**, *3*, 15–25. [CrossRef]
43. Tešić, D.; Božanić, D. Optimizing Military Decision-Making: Application of the FUCOM– EWAA–COPRAS-G MCDM Model. Acadlore Trans. *Appl. Math. Stat.* **2023**, *1*, 148–160. [CrossRef]
44. Tavana, M.; Shaabani, A.; Valaei, N. An integrated fuzzy framework for analyzing barriers to the implementation of continuous improvement in manufacturing. *Int. J. Qual. Reliab. Manag.* **2021**, *38*, 116–146. [CrossRef]
45. Kizielewicz, B.; Bączkiewicz, A. Comparison of Fuzzy TOPSIS, Fuzzy VIKOR, Fuzzy WASPAS and Fuzzy MMOORA methods in the housing selection problem. *Procedia Comput. Sci.* **2021**, *192*, 4578–4591. [CrossRef]
46. Sałabun, W.; Urbaniak, K. A new coefficient of rankings similarity in decision-making problems. In Proceedings of the Computational Science–ICCS 2020: 20th International Conference, Amsterdam, The Netherlands, 3–5 June 2020; Proceedings, Part II 20. Springer International Publishing: Berlin/Heidelberg, Germany, 2020; pp. 632–645.
47. Więckowski, J.; Kizielewicz, B.; Shekhovtsov, A.; Sałabun, W. How Do the Criteria Affect Sustainable Supplier Evaluation?—A Case Study Using Multi-Criteria Decision Analysis Methods in a Fuzzy Environment. *J. Eng. Manag. Syst. Eng.* **2023**, *2*, 37–52. [CrossRef]