

Article

Multi-Criteria Analysis of Potential Applications of Waste from Rock Minerals Mining

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Featured Application: The paper presents a two stage, multicriteria-based methodology for evaluation of mining waste potential use that can be applied to any type of mining waste site.

Abstract: The article describes the research on the analysis of the economic use of mining and processing waste produced and stored on the premises of active mining plants exploiting rock raw materials in the context of the reduce-recycle-reuse (3R) concept. To assess the potential economic applications of the investigated wastes, a two-stage methodology based on a multicriteria analysis using the Analytical Hierarchy Process (AHP) algorithm was proposed. Preliminary research produced an inventory of active mining plants storing mining and processing waste on their premises (62 locations). Then, preliminary qualitative analysis was carried out to assess mining waste locations at the environmental and social level consistent with the idea of circular economy—CE (20 locations). Next, in the first stage of the multi-criteria analysis, six directions of economic use of the investigated waste were analyzed and their significance was determined. These directions are use in road and railroad construction, construction, agriculture, reclamation and development of post-mining areas, food industry, and storage at landfills of mining and processing waste on the premises of a mining plant. In the result of the assessment of potential economic applications of mining waste, recommendations for directions of economic use were obtained for the six highest classified mining waste sites. The recommendations were determined in the second stage of multi-criteria analysis by deriving the local preferences (waste sites) for the alternatives (waste uses).

Keywords: rock minerals; mining waste; reuse; multicriteria analysis; AHP; Poland

1. Introduction

Mineral resources constitute the foundation of development of every economy in the world. Thus, the demand for them is constantly growing. Taking into account that along with the growth of mining, the process of mineral resources treatment also increases, the amount of mining and processing waste is also growing. According to Eurostat, 632 million Mg of mining waste was generated in the EU countries. Poland is one of the largest producers of mining waste. Approx. 11.2% of globally produced waste is generated here [1]. Moreover, in the case of mineral resources management, there is also a problem consisting of depletion of resources from existing sources, in connection with the linear model of production and use of mineral resources. Therefore, emphasis was put on the rational management of resources, which in consequence results in attempts to close the cycle of extraction and processing of raw materials into the closed circuit (circular economy) and, as a result, on the search for the management possibilities of mining and processing waste. The basis of the circular economy

concept is the optimization of the use of resources in accordance with the so-called 3R principle (reduce-recycle-reuse) [2,3].

Territorial scope of the research carried out in the publication concerned the area of Lower Silesia, which is located in the southwest part of Poland (Figure 1). This region is the most interesting in Poland in terms of rich accumulation of rocks with diverse genesis and age. Additionally, over 90% of minerals extracted in Poland for the production of construction and road elements originate from deposits located in the Lower Silesia region [4]. The subject of the research are active mining plants, which extract and process rock raw materials, such as bentonites, dolomites, ceramic and refractory clays, crushed and dimension stones, vein quartz, phyllite and mica schists, magnesites, sands, and gravels. The period covered by the study concerned the years 2010–2016. The research method used for the purpose of collecting and analysing the source data was the method of examining documents, consisting of collecting, selecting, describing and interpreting the facts contained in it. The research was limited to establishing the actual state of affairs, which the sources consisted of data archived in the period 2010–2016 from databases of the Marshal's Office, District Mining Office, Polish Geological Institute, Provincial Inspectorate for Environmental Protection and the Main Office of Geodesy and Cartography. Within the research, the quantitative and qualitative analysis of waste was carried out. The quantitative analysis concerned obtaining information on the quantity and location of post-mining waste and it was carried out in the publication of Blachowski et al. [5], whereas the qualitative analysis allowed to recognize the nature and the generic composition of the deposited waste [6]. As a result, the methodology of multicriteria analysis was used in this publication in order to present the recommendation concerning possibilities of waste management, assuming the use of known around the world and/or new technologies.



Figure 1. Map of Poland with the research area (Lower Silesia) marked.

The methodology of multicriteria analysis applied in our study relies on the Analytical Hierarchy Process (AHP) methodology proposed by Saaty [7]. It is one of multicriteria decision analysis methods that can be applied to a wide range of different decision-making problems, such as selection, evaluation, benefit–cost analysis, allocation, planning and development, priority and ranking, and decision-making. An extensive review of its applications was presented for example in publication Vaidya et al. [8]. With respect to waste management, the AHP methodology has been used to support decisions regarding selection of suitable municipal waste sites e.g. [9–11]. With respect to mining waste management, [12] applied this methodology for the selection of sites suitable for stone (solid waste) disposal facilities on a case study in Greece, and [13] applied Analytical Hierarchy Process (AHP) and Technique for Order Preference by Similarity to Ideal Solution (TOPSIS) in analysis of strategies for waste management in iron mines in India. Whereas, [14] used it for analysis of the environmental impact of tailing ponds in ore mining area in Northern Kosovo. Other examples of the method's applications connected with mining include mineral processing site selection [15], selection of remedial

alternatives for mine sites [16], and multicriteria assessment of the technologies of management of waste from coal mining sites [17].

In our study, which is a follow-up of the research on quantitative and qualitative analysis of waste from rock minerals mining [6], we aimed at multicriteria (AHP) determination of the suitability of mining waste sites for new development with respect to different criteria (potential uses of waste from rock mineral mining).

2. Preliminary Qualitative Analysis

A precise analysis of this issue was conducted in the work of [6] in two dimensions: environmental and economic (CE idea). The first criterion of this analysis consisted of environmental conditions regarding the arduousness of waste utilization. The basic criterion here was the recognition whether the examined waste is considered dangerous or whether it is the so-called neutral waste. The second criterion was the location of the examined mining waste treatment facility. Whether the given facility is located in legally protected areas (e.g., national parks, nature reserves, protected landscape areas, NATURA 2000 areas, etc.) or not. This criterion also took into account the occurrence of the Main Underground Water Reservoirs.

In the scope of economic criteria, the first examined aspect was the set of raw materials that are essential for the Polish economy [18]. Therefore, the following were recognized as essential among the rock raw materials: kaolinite clays, crushed and dimensions stones, kaolins, sands and gravels, feldspar raw materials and glass sands. The second aspect taken into account in economic criteria was the type of waste with potential economic significance. Of course, the amount of given waste was also taken into account. Considering the literature analysis, the economic significance is also assigned to the waste, for which it is possible to use them e.g., in reclamation, agriculture, food industry or production of light aggregates. The research also took into account the possible directions of applications of rock raw material waste, which can be grouped in the following manner:

- Industrial use of clays: the clays mainly consist of loamy minerals, such as kaolinite, illinite, montmorillonite, and other aluminosilicates, as well as other various components, e.g., quartz grains, apatite, granite, iron hydroxide, etc. The potential uses include: multifunctional sorbent-fertilizers designed for the reclamation of sands [19,20], feed additives, which constitute an important group of preparations in breeding, such as peat humus, zeolites, kaolins, bentonites, and others having a positive effect on production indicators [21,22], insecticides, and fungicides in order to increase the effectiveness of pesticides [23–26], food industry use of bentonite clay for storing fruit and vegetables in households [27], and environmental protection use of clay as an absorbent to remove heavy metal ions and purification of industrial and drinking water [23,28].
- Rock meals: basalt, granite and serpentine materials from mining waste can be used to produce rock meals, which are created from grinding of the rock. Such meals can be used to improve soil properties by enriching it with minerals, such as calcium, potassium, and magnesium. E.g., comprehensive “remineralisation” of the soil substrate with basalt meal [29]. Granite meals are useful on heavy soils as well as light, sandy soils, which are poor in loamy minerals because they increase the water capacity of soils, particularly in the humus layer and include many necessary macro-, micro-, and ultra-microelements, which are necessary for the proper growth of plants. In addition, these rock meal plays a sanitary role, preventing the spread of diseases and pests. The serpentinite meal can provide the soils with many microelements, among others iron and phosphorus [30,31].
- For the production of light, inferior. or hydro-technical aggregates: use of granite waste for the production of aggregates, which allowed to strengthen the strength of aggregates produced and eliminate flux and apply it to various structures (for example, stabilization of landslips and slopes, strengthening of underwater slopes, etc.) [32].

- As a granulate supporting cultivation of plants: granulate contains rock siliceous meal selected from the group of basalt, feldspar, or amphibolite meals. The granulate remains on the soil in unchanged form until atmospheric precipitation, and then it gradually disintegrates and returns to silty form and gradually penetrates into the soil structure [33].
- As fillers for thermoplastics: in the scope of this technology, the gabbro waste can be used as an attractive solution for obtaining inexpensive composites with good thermal and mechanical properties [34].

The research of known case studies and literature [19–34] on environmental and economic aspects allowed to identify the following criteria to be proposed for analysis:

Environmental criteria:

- Criterion **K1**—waste category—dangerous or inert,
- Criterion **K2**—location in protected natural areas and Main Underground Water Reservoirs,

Economic criteria:

- Criterion **K3**—raw materials that are essential for the economy,
- Criterion **K4**—occurrence above 10 000 thousand Mg,
- Criterion **K5**—occurrence of loamy raw materials (use e.g., in agriculture or in the food industry),
- Criterion **K6**—occurrence of raw materials as a source of potassium—meals and small granite fractions,
- Criterion **K7**—occurrence of raw materials as a source of magnesium—serpentine, basalt, syenite.

Application of the abovementioned criteria in the qualitative analysis led to a selection of 20 sites listed in Table 1 for further analysis. Location of all the sites is shown on the map in Appendix A. Example mining waste treatment facility is shown in Appendix B. The results of conducted analysis indicated that the selected objects have waste containing: clay, gangue with overgrown weathered granite, basalt, granite, overburden containing loamy raw materials, serpentine, sands contaminated with clay, inferior quality rock raw material, crushed stone (e.g., granite, gabbro, serpentine, basalt).

The multicriteria analysis consisted of two stages, where stage one (A) provided ranking of mining waste sites (Table 1) and stage two (B) allowed to determine the most suitable potential uses for the six highest ranked waste sites.

Table 1. Ranking of mining waste sites [6].

Rank	Mining Site	Mineral	Weighted Score
1.	Krzeniów	basalt	2.6542
2.	Lubień	basalt	2.3808
3.	Grabina Śląska-Kam. 15/27	granite	2.0890
4.	Gniewków	granite	1.9811
5.	Boguszyce	sands and gravels	1.9298
6.	Romanowo Górne	marble	1.9022
7.	Rogoźnica II	granite	1.8732
8.	Byczeń I	sands and gravels	1.8722
9.	Stróża Górna II	sands and gravels	1.8722
10.	Sulików	basalt	1.8640
11.	Słupiec-Dębówka	gabbro	1.8640
12.	Janina I	sandstone	1.7326
13.	Rybnica Leśna	melaphyre	1.6864
14.	Doboszowice I	gneiss	1.6564
15.	Radostów Średni II, III	sands and gravels	1.6564
16.	Braszowice	gabbro	1.6482
17.	Jenków	schist	1.5209
18.	Nowy Waliszów – soczewka C	marble	1.5168
19.	Połom	limestone	1.5168
20.	Rędziny	dolomite	1.4892

3. Methodology

As was mentioned, the methodology of multicriteria analysis applied in our study relies on the Analytical Hierarchy Process (AHP) [7]. Our approach consists of two stages (Figure 2). In the first one (stage A), which has been described in [6], we identified, the above-mentioned mining waste criteria (K1–K7) based on their economic and environmental characteristics (A1) and employed the AHP methodology to calculate weights of these criteria (A2). Then, we allocated points to each of the 20 mining waste sites for each of the proposed criteria from a 3-point scale, where 1 point indicated the least suitable to be used for industrial purposes and 3 was the most likely to be used for industrial purposes (A3). In the last (A4) part of this stage, we calculated the weighted score for each mining waste sites. This provided the final ranking of mining waste that should be considered for potential new use (Table 1).

In the second stage (B), which is the main subject of this paper, firstly we identified the main potential mining waste uses (B1). Next, we constructed a three-level AHP decision hierarchy structure, which was used to determine weights of potential mining waste uses (B2), weights of alternatives (mining waste sites determined in stage A) with respect to each of the potential mining waste uses (B3), and the final score of each site (B4).

As previously [1], we determined the weights based on seven responses that were provided by the authors and four additional experts from specializations such as spatial planning, environmental protection, resource management, and mining administration. The experts represent regional institutions such as the Institute for Territorial Development (Marshal Office), the District Mining Office, the Regional Inspectorate of Environmental Protection, and Wroclaw University of Science and Technology. For the calculations, we employed the AHP template proposed by Goepel [35].

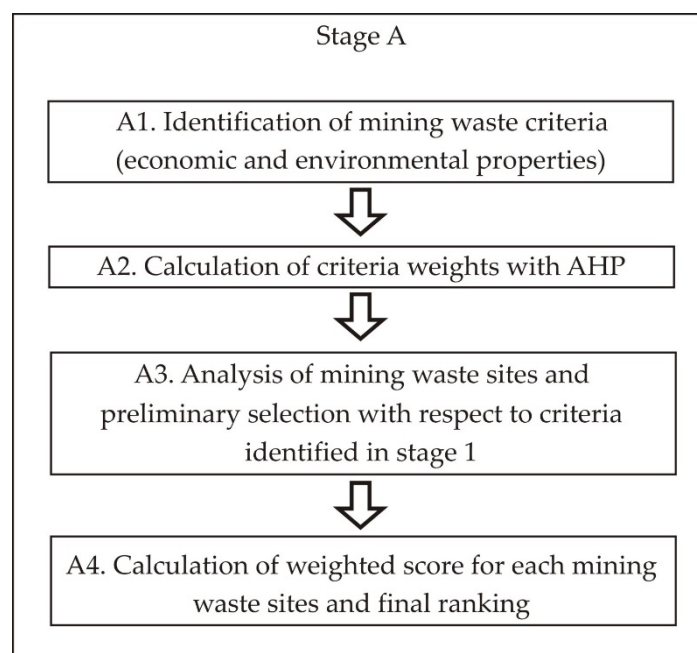


Figure 2. Cont.

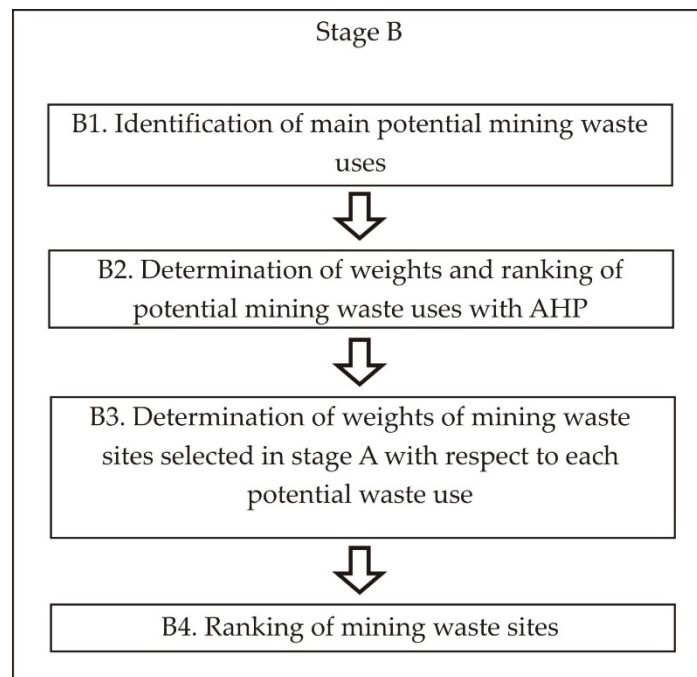


Figure 2. General scheme of the methodology for multicriteria analysis of mining waste potential of new use for the selected sites.

In detail, Part B of our study, according to the AHP theory [7,36], consists of the following steps:

- a) developing the model,
- b) deriving weights for the criteria,
- c) checking the consistency,
- d) deriving local preferences for the alternatives,
- e) deriving overall priorities and making the final judgement.

Step a) involves constructing a hierarchy to analyse the decision. The AHP decision model for selecting waste for reuse is structured into a hierarchy of goal, criteria, and alternatives (Figure 3). In the case where the goal is to select the deposited mining waste for new use, the criteria are potential uses of mining waste, and the alternatives are the individual mining waste sites.

Step b) consists of deriving weights of the criteria, and the importance of criteria is compared pairwise with respect to the desired goal to derive their weights.

Next, in step c), check of the consistency of judgments is performed; it involves a review of the judgments in order to ensure a reasonable level of consistency in terms of proportionality and transitivity.

Step d) consists of deriving the local preferences for the alternatives. Priorities for alternatives are derived separately for each criterion following the same method as in step b). Consistency check is also carried out.

In step e), overall priorities of the alternatives are calculated, i.e., the obtained alternative preferences are combined as a weighted sum to take into account the weight of each criterion. The alternative with the highest overall priority constitutes the best choice.

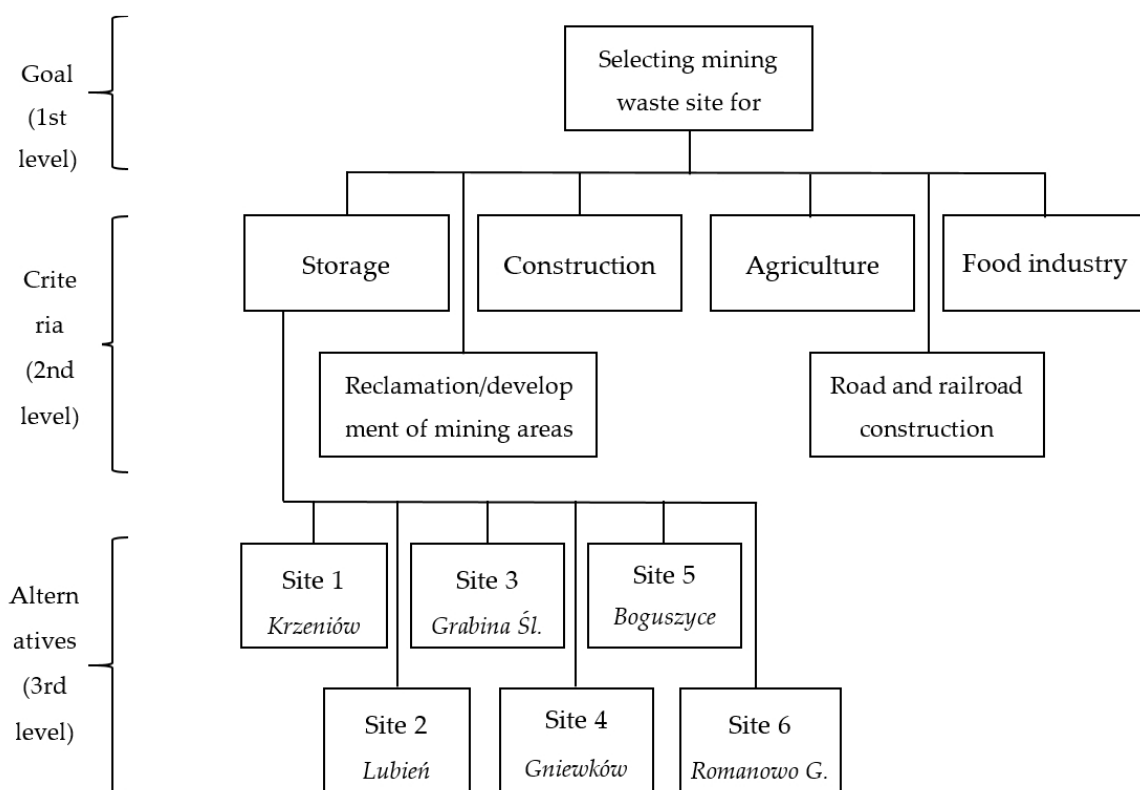


Figure 3. Decision hierarchy for waste site selection (3rd level repeats and is shown for one criterion only).

Thus, if n is the number of analysed criteria, then the AHP comparison procedure is as follows:

- to construct a $n \times n$ pairwise comparison matrix m for analysed criteria, where a_{ij} denotes entry in the i th row and the j th column of matrix m ,
- a_{ij} states the preference score of criterion i to criterion j using the nine-integer value scale suggested by Saaty [37], where:
 - 1 denotes that criteria i and j are of equal importance,
 - 3 is moderate importance of i over j ,
 - 5 is strong importance of i over j ,
 - 7 is very strong importance of i over j ,
 - 9 denotes that criterion i is extremely more important than criterion j , and
 - 2, 4, 6, and 8 are intermediate, optional, values.
- the entries of preference score a_{ij} and a_{ji} must satisfy the following constraint of Equation (1):

$$a_{ij} \times a_{ji} = 1 \tag{1}$$

- to establish a normalized pairwise comparison matrix m , the sum of each column must be equal to 1. This can be obtained using Equation (2) to calculate \bar{a}_{ij} for each entry of the matrix \bar{m} [38],

$$\bar{a}_{ij} = \frac{a_{ij}}{\sum_{l=1}^n a_{il}}, \tag{2}$$

- to obtain the relative weights, the average across rows is computed using the Equation (3); for each element, the relative weight is within the range of 0 to 1 and a higher weight shows a greater influence of a given element (criterion) [37],

$$w_i = \frac{\sum_{l=1}^n \bar{a}_{ij}}{n}, \tag{3}$$

A test of the degree of consistency of the derived weights is performed to check the consistency of the experts' judgements. It involves a calculation of the Consistency Ratio (CR), which indicates the probability that the matrix values have been randomly generated. According to Saaty [7], a matrix that has a consistency ratio greater than 0.10 should be re-evaluated.

For controlling the consistency of the estimated weight values, the consistency ratio (CR) is calculated as follows [36]:

- calculate the eigenvector and the maximum eigenvalue for matrix m ,
- next, calculate an approximation to the Consistency Index (CI) according to Equation (4):

$$CI = \frac{\lambda_{max} - n}{n - 1}, \tag{4}$$

where

- λ_{max} is the maximum eigenvalue of the comparison matrix,
- n is the number of criteria.

The Consistency Ratio is calculated from the Equation (5),

$$CR = \frac{CI}{RI}, \tag{5}$$

where,

- RI is the random consistency index that varies according to the number of criteria in a comparison (n).

As mentioned above for $CR \leq 0.10$, the degree of consistency is considered satisfactory; otherwise, there are serious inconsistencies in the pairwise comparison and the AHP may not return meaningful results.

The above procedure was used twice, for deriving weights of criteria (mining waste uses) and for deriving the local preferences (sites with deposited waste with respect for each criterion). Each of the authors and experts prepared matrix with pairwise comparison for criteria and six matrices for with pairwise comparison for alternatives with respect to each criterion. These matrices were used to establish the weighted scores of criteria and alternatives.

Overall priorities of the alternatives were calculated as a weighted sum (S) of the products of criterion weight and local preference relative to this criterion, Equation (6):

$$S = \sum_{i=1}^n Cw_i \times Aw_i, \tag{6}$$

where,

- Cw_i is the criterion weight,
- Aw_i is the preference of alternative relative to that criterion,
- n is the number of criteria.

4. Results

Based on the review of literature [19–34], expertise of the authors and knowledge of the experts involved in the study, the following potential applications of mining waste were identified:

- Use in road and railroad construction,
- Use in construction,
- Use in agriculture,
- Use for reclamation/development of post-mining areas,
- Use in the food industry,
- Storage of mining waste.

4.1. Results for Deriving Weights for the Criteria

Results of AHP calculations to determine weights of potential uses of waste from rock minerals mining and processing as compared by the experts are presented in Table 2.

Table 2. Weights of criteria (potential waste uses).

Position	Criterion Name	Weight [%]
1.	Use in road and railroad construction	32.6
2.	Use in construction	25.0
3.	Use in agriculture	15.2
4.	Use for reclamation/development of post-mining areas	15.0
5.	Use in the food industry	9.2
6.	Storage of mining waste	2.9

Deposition of mining waste is considered as the least preferable use of waste from rock minerals mining and processing (2.9%), whereas within the remaining five identified possible applications of waste from rock minerals, the use in road and railroad construction is considered as the most preferable (32.6%), followed by use in other forms of construction (25.0%). Use in agriculture, as well as use for reclamation or development of post-mining areas, are considered to be similarly applicable with weights of 15.2% and 15.0%, respectively. Use of waste from rock minerals mining in the food industry accounts for 9.2% of the total weight.

For six criteria ($n = 6$), the Random Index (RI) equals to 1.24 [38], and we obtained the Consistency Ratio (CR) of 1.8%. This is well within the accepted limits ($\leq 10\%$). The consensus of experts equals to 62.5%.

4.2. Results for Deriving Local Preferences for the Alternatives

Evaluation of local preferences for the alternatives (mining waste sites) with AHP produced the results presented in Table 3.

Table 3. Weights of local preferences with respect to potential waste uses (criteria).

Alternatives (Waste Sites)	Storage	Reclamation/Development	Agriculture	Food Industry	Road/R-Road Construction	Construction
Site 1. Krzenów	0.058	0.097	0.242	0.025	0.211	0.149
Site 2. Lubień	0.197	0.136	0.093	0.260	0.067	0.080
Site 3. Grabina Śl.	0.143	0.262	0.258	0.111	0.308	0.309
Site 4. Gniewków	0.136	0.206	0.276	0.182	0.287	0.318
Site 5. Boguszyce	0.163	0.171	0.070	0.192	0.063	0.073
Site 6. Romanowo	0.303	0.128	0.061	0.230	0.064	0.072

The Consistency Ratios (CR) for pairwise comparisons for alternatives with respect to criteria vary from 0.5% to 3.8% and are within the required limits ($\leq 10\%$). The lowest value (0.5%) was obtained for the use in construction criterion and the highest (3.8%) for the use in agriculture criterion. The highest consensus (90%) of the seven experts was achieved for the pairwise comparison with respect to the use in road and railroad construction criterion, whereas the lowest one (73.3%) for the reclamation/development of post-mining area criterion.

The overall priorities for the alternatives (waste sites) given the weight of each mining waste use criteria (synthesis of the AHP model) are presented in Table 4.

Table 4. Results of overall priority calculations.

Position	Alternatives (Waste Sites)	Overall Priority [%]
1.	Site 3. Grabina Śl.	27.1
2.	Site 4. Gniewków	26.7
3.	Site 1. Krzeniów	16.1
4.	Site 2. Lubień	10.6
5.	Site 5. Boguszyce	9.8
6.	Site 6. Romanowo G.	9.7

5. Discussion and Recommendations Resulting from the Performance of Multicriteria Analysis

Results of the model synthesis indicate that two of the analysed sites, i.e., Grabina Śl. and Gniewków are the most attractive for potential new application of the deposited waste with 27.1% and 26.7% of the total score, respectively. The site that ranked third, Krzeniów, obtained approximately 10 percent point lower score (16.1%) and the remaining three sites were evaluated at a lower and nearly the same score of 10%. Results in Table 4 provide overall priorities for these sites. The highest position of the Grabina Śl. and Gniewków sites arises from the fact that the material store there is most suitable for new use in the two most preferred potential uses of such waste, i.e., road and railroad construction and construction industries (Table 2). However, if we chose to assess potential of these six analysed mining waste sites for a different preferred application, then we should consider these results jointly with the determined weights of local preferences with respect to the potential waste uses (Table 3). For example, if we consider looking for mining waste site with the greatest potential for use in the food industry, then site 2 Lubień and site 6 Romanowo are the most attractive, and in the case of choosing to store the deposit, site 6 due to its characteristics is the least suitable for uses other than deposition.

Recommendations resulting from the conducted multicriteria analysis mainly arise from the generic composition of the waste located in the examined facilities. The conducted research indicated the most attractive potential application of stored waste for the given facilities, which is presented in Table 5. The landfills Grabina Śl. and Gniewków contain loamy material and weathered granite. Their attractiveness is associated with the occurrence of granite, which can be used in the production of light aggregates or hydro-technical stone. Research concerning the use of granite waste for the production of light aggregates indicated an increase in the strength of obtained aggregates by approx. 1.5 times more than aggregates produced with the use of silica [32]. On the other hand, the hydro-technical stone can be used to stabilize landslides or slopes or to strengthen underwater slopes. Another highly rated application for granite waste materials may be their use for the production of rock meals. In the case of discussed landfills, it is also attractive to manage the loamy raw materials located in these facilities. This type of waste is also located in three facilities, which were assessed at the lowest level I, and these are Lubień, Boguszyce, and Romanowo. The possibilities of managing waste containing loamy raw materials apply to clays consisting mainly of clay minerals, such as kaolinite, montmorillonite, and other silicates, as well as quartz, apatite, granite, or iron hydroxide. These raw materials are characterized by special properties, such as high capillarity, unique rheological properties, hardening, plasticity, high swelling ratio, and they can be widely used in various branches of the

industry. Thus, one of the possibilities for their management is to use them for storing fruit and vegetables in households. The conducted research indicated that the use of clay may be the best ecological and cost-free storage mechanism, compared to the storage in warehouses and cold stores. Another recommendation for the application of the discussed waste group is the possibility of their use for the production of sorbent-fertilizers, used for the reclamation of lands after the exploitation of sands. Moreover, the bentonite occurring in montmorillonite rocks can be used in soil fertilization, due to its moisture retention properties and the slow release of fertilizer elements. As a consequence, the bentonite ensures greater flexibility and improvement of the soil strength as well as increased water impermeability. Another solution may be the use of loamy waste raw materials as feed additives. The use of aluminosilicates for the feeds, e.g., kaolin of FKW type or zeolite of AA type, in the feeding of broilers and breeding of laying hens, has a positive impact on production rates, as well as on the quality of eggshells [21,22].

The Krzeniów landfill, which is located in the third position, has waste in the form of gangue with basal overgrowths and a 0–8 mm basalt fraction. Mainly, this waste should be used in agriculture as basalt meal. Meals of this type fulfil the function of a measure improving the properties of soil due to the relatively low content of minerals (main and trace). The distinct advantages of basalt meals include non-toxicity, inability to overdose, not being subject to elution by groundwater and not having a shelf life or maximum storage period [29].

Table 5. Recommendations of potential possibilities for using waste regarding results of overall priority calculations and weights of local preferences with respect to potential waste uses.

Name of the Mining Plant	Waste	Hierarchy of Potential Use
Grabina Śl.	weathered granite	for the manufacture of hydro-technical stones for the manufacture of light aggregates for the manufacture of aggregates of the inferior quality granite rock meal—for improvement of soil properties
	clay	sorbent-fertilizer of montmorillonite rocks for reclamation use of bentonite for soil fertilization use of kaolin as a feed additive use of bentonite clay in the food industry (for storing fruits and vegetables)
Gniewków	granite saprolite	for the manufacture of light aggregates granite rock meal—for improvement of soil properties for the manufacture of light aggregates
	clay	use of bentonite for soil fertilization use of kaolin as a feed additive sorbent-fertilizer of montmorillonite rocks for reclamation use of bentonite clay in the food industry (for storing fruits and vegetables)
Krzeniów	gangue with overgrowths of weathered basalt basalt-fraction 0–8mm	rock (basalt meal) for improvement of soil properties
Lubień	clay	use of bentonite clay in the food industry (for storing fruits and vegetables) sorbent-fertilizer of montmorillonite rocks for reclamation use of bentonite for soil fertilization use of kaolin as a feed additive
Boguszyce	clay	use of bentonite clay in the food industry (for storing fruits and vegetables) sorbent-fertilizer of montmorillonite rocks for reclamation use of bentonite for soil fertilization use of kaolin as a feed additive
Romanowo Górne	overburden	use of bentonite clay in the food industry (for storing fruits and vegetables) sorbent-fertilizer of montmorillonite rocks for reclamation use of bentonite for soil fertilization use of kaolin as a feed additive

6. Conclusions

In the paper, we presented a methodology for the evaluation of mining waste sites with respect to preferred new uses. The methodology is based on two-staged multicriteria analysis with Analytical Hierarchy Process (AHP) method. The methodology was preceded by preliminary qualitative analysis that identified the economic and environmental criteria for assessment of mining waste and allowed to evaluate potential of rock mineral mining waste in the Lower Silesia region of Poland. In the results of multicriteria analysis, we determined the most preferred new applications of mining waste and determined the weights of local preferences with respect to these potential waste uses. Use in the construction, as well as road and railroad construction industries were the most preferred new applications, while the storage and the use in remediation and development of post-mining areas the least preferred.

The research results enabled to present the priorities for the use of waste in the examined facilities. The highest hierarchy was assigned to the granite and basalt waste raw materials located in the following facilities: Grabina Śl., Gniewków, and Krzeniów. The remaining ones (Lubień, Boguszyce, and Romanowo Górne) constitute facilities containing loamy waste raw materials and overburden also with the content of clay. Recommendations concerning the application directions of the waste located in the six ultimately examined facilities result from waste materials found in these facilities (Table 4). The research results (Table 5) indicated that in the first place, the granite waste raw materials should be recommended for the use in construction and railway and road engineering (granite waste). They may be also used for the production of hydro-technical stones, light aggregates or lower quality aggregates. Further, the granite waste can be used as feldspar meals that improve soil quality, whereas the basalt waste raw materials should be mainly used to improve the quality of soil as basalt meals. The management of loamy waste should be considered in the directions of sorbent-fertilizer production for the reclamation of sands, food industry, agricultural industry, and as a feed additive.

Recommended facilities that own mining waste can be indicated as facilities for which a circular economy should be used. Thus, research on the economic analysis of waste generated by active mining plants is very important in order to inventory them, along with the indication of the best method of their economic use. It seems that, in order to encourage entrepreneurs to introduce changes in the technologies of extracting and processing of rock raw materials, which allow us to use the principle of use of resources (particularly waste occurring in the technological process), in accordance with the 3R principle, it is necessary to ensure cooperation at the regional level (through various financial and organizational programs), as well as the cooperation of entrepreneurs, scientific units and territorial units. An example of such program is the project "Lower Silesian Voucher for Innovations," which is offered within the Regional Operational Program of the Lower Silesia Province 2014–2020, co-financed from the European Regional Development Fund, which is aimed at supporting the cooperation of Lower Silesian micro, small, and medium enterprises with scientific units, which will result in the improvement of enterprise's business activity, thanks to the knowledge flowing from the scientific communities.

The proposed methodology can be applied to other mining waste sites, as well as other mining regions and other mining waste types (e.g., metallic).

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Appendix A

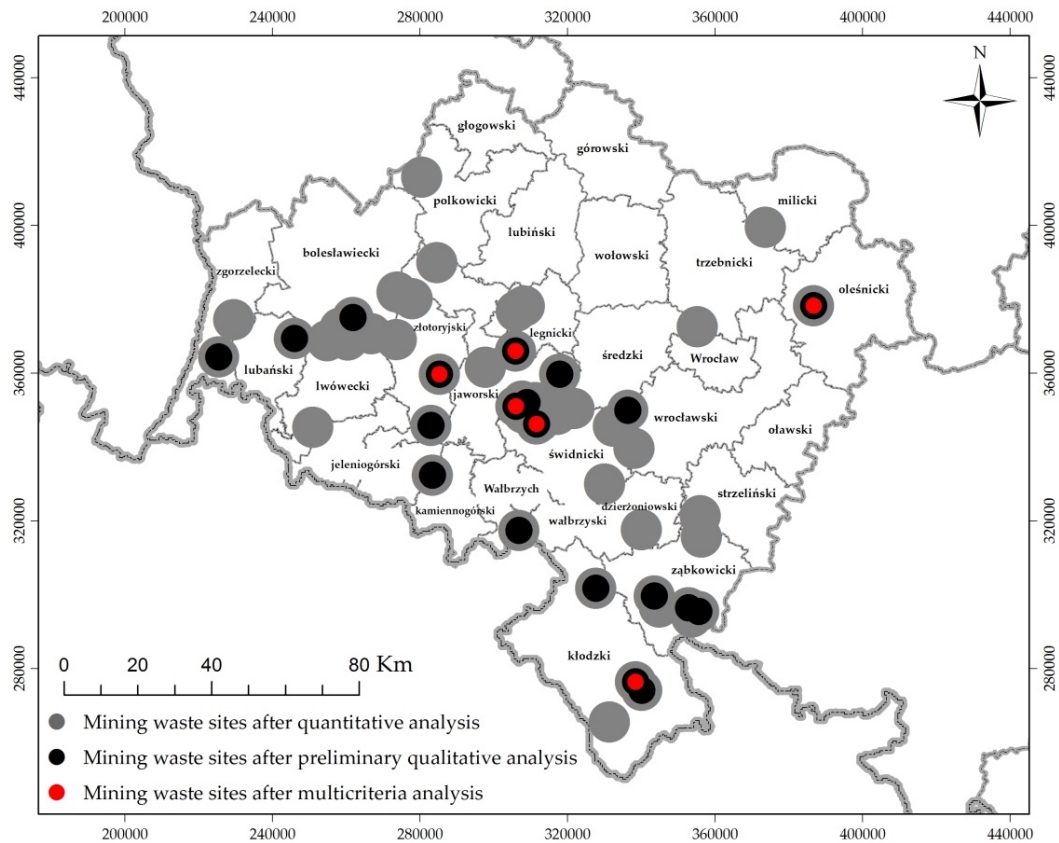


Figure A1. Location of waste treatment facilities.

Appendix B



Figure A2. Mining waste treatment facility of the Gabbro Mine “Braszowice” – on the left: completed, on the right: under construction (photo U. Kaźmierczak, 2017).

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