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MULTICRITERIA ANALYSIS FOR THE DETERMINATION OF THE EXPLOITABILITY INDEX OF INDUSTRIAL AGGREGATE OUTCROPS

Geographical Information Systems have become essential tools for land analysis and the subsequent decision making in many fields of human activity. In the field of mining, GIS applications have appeared in ore deposit modelling, environmental pollution, or planning of mining spaces. In this research, the powerful multicriteria tools of GIS platforms have been applied for the determination of an index that has been called "Exploitability Index". This index allows analyzing a series of outcrops of industrial aggregates, to help in the selection of the most adequate one to be enhanced from a mining approach. The multicriteria analysis has been applied for its determination, and as a result of this research, a model is proposed. The main criteria that condition the decision have been established in this model, along with their subsequent hierarchization and their weighting. The proposed model is applied to a specific case: the analysis of a series of outcrops of industrial aggregates (ophites) in Cantabria, Spain. After defining the Exploitability Index for those ophitic outcrops, it has been observed that the only deposit that has been classified as very suitable for its exploitation is the only one that has been really exploited, supporting the proposed methodology.

Keywords: GIS; Exploitability Index; multicriteria analysis, industrial aggregates

1. Introduction

Geographic Information Systems (GIS) have provided an essential tool for decisions making in cases in which the thematic, spatial and time information have a special relevance. These decisions can define the success of a project, the optimal location for facilities, improvements in

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productivity, *etc*. All the foregoing justifies the current importance of these tools. GIS technology can be applied for scientific research, resources and goods management, archaeology [1], environmental impacts assessment [2], land planning [3], landscape and sociology [4], inventories and mining logistics [5].

The publications, studies and research that has been developed about the application of GIS in mining are mainly targeted on topics such as environmental aspects and preservation [6,7] or enhancement of mining spaces [8]. It is relatively easy to find studies about potential uses of land in abandoned mining areas, the generation of evolutive cartography in terms of density of mining exploitation in different countries, pollutant spreading due to mining accidents, analysis of risk of pollution of water reservoirs in coal areas, the mapping of locations that can be affected by subsidence, the development of 3D models of geologic structures, or the creation and update of mining registries.

Considering the use of natural resources, there are GIS applications for the exploitation of underground waters, the location of gravels and the extraction of sands, the analysis of distribution of metallic ores (with statistical tools such as kriging or inverse distance weighting). Dellero and El Kharim [9] propose a GIS tool that is aimed at determining potential areas for the location of limestone quarries in Morocco, by the development of a multicriteria analysis. Geometric, legal and social factors are considered and differently weighted, but this multicriteria analysis is only targeted to the assessment of environmental impact, with the generation of a model that comprises four levels of exploitability with increasing levels of environmental impact. Two different algorithms are applied with GIS tools, and the results are compared.

Other recent applications, related to mining surveying and evaluation, have been presented. Along with machine learning methods [10], Boolean logic, hydrogeological analysis [11], or geophysical data [12], GIS tools have been applied to predict the spatial distribution of undiscovered deposits of different types of mineral resources. Another recent use of GIS in the field of mining is the evaluation of the economic potential and sustainable exploitation of lignite deposits through their spatial analysis [13].

This research is aimed at determining an Exploitability Index (I_e) with GIS tools. It is a numerical value that, according to several criteria, allows hierarchizing in a rational way each one of the industrial aggregate deposits for their potential exploitation. It permits decision making for deposit exploitation, with the advantages that it implies. The foregoing seeks developing a logic and rational analysis that can be applied by mining enterprises or the Administrations in charge of granting the exploitation permits.

As presented in this research, I_e can be used as a criterion for the election for mining exploitation of outcrops whose commercialization is restricted and/or economic value is scarce. The type of deposits that are considered are mainly industrial aggregates, as others exhibit a better chance of commercialization or higher economic values and, therefore, the criteria for selection are completely different to those presented in this research.

2. Methodology and introduction to the topics

The methodology to hierarchize outcrops requires at first an integration of the potential exploitation within the territorial context: those with lower environmental impact must be prioritized. In order to do so, the method proposed by Díaz de Terán and González Lastra [14] has been adopted. It catalogues the different outcrops according to their possibilities of exploitation

TABLE 1

Methodology for the evaluation and hierarchization of rock outcrops
for their exploitation [14]

Criteria for the hierarchization of outcrops		
Definition of requirements	Geologic Characteristics	Rock type Lateral and vertical uniformity Grade of rock weathering Fractures and joints Overburden thickness Cavities Natural slopes Other features
Inventory of characteristics	Internal Economic Characteristics	Reserves Type of exploitation that is suitable for the deposit
	External Economic Characteristics	Accessibility of the deposit Demand Proximity to commercial areas of consumption Type of market to which the product is targeted
	Social-environmental Characteristics	Impact of the exploitation on the environment Future uses of potential implementation in the area Current uses of the area Proximity of urban areas
Classification of requirements	Requirements	Necessary requirements Desirable requirements Additional requirements Final requirements

and their socioeconomic interactions. Table 1 schematizes all the criteria that are used for the hierarchization.

Following the methodologies proposed by Oliveira Sousa [15] and Muñoz de la Nava et al. [16], six parameters were demonstrated to be the most important ones by field studies and economic considerations to characterize the exploitability: quality of material (rock properties), macro-fracturing, geographic location of the outcrop (proximities to population and accesses), size, land morphology and grade of superficial weathering.

As a result of this research and its combination with the described methods, a new factor has been introduced, the railway access, given its importance in the case of aggregates. The factor of macro-fracturing has been removed as it lacks interest in the case of aggregates. The environmental impact is emphasized, given the social concern that exists when facing the establishment of new mining sites.

Six fundamental criteria have been set, with a series of V_i values (coefficient of hierarchization) according to spatial and observational field data. Ranks that vary between the most favorable ($V_i = 0$) to the most adverse ($V_i = 4$) have been considered for every criterion. In addition to this, they are affected by a coefficient (K_i) that depends on the relative weight that can be attributed to each criteria when assessing the different outcrops. It is particular for each of them (Table 2). The value of K_i considers the special features of the rocks and the social-economic conditions of the surrounding area.

TABLE 2

Relative importance of K_i (correcting coefficient) and V_i (hierarchizing coefficient)

Criterion	K_i \ V_i	**0**	**1**	**2**	**3**	**4**
Land morphology	**1**	Very Low	Favorable	Acceptable	Adverse	Very Adverse
Road accesses	**2**	Very Good	Good	Acceptable	Bad	Very Bad
Railway accesses	**3**	Very Good	Good	Acceptable	Bad	Very Bad
Weathering	**2**	Very Low	Low	Acceptable	High	Very High
Reserves	**3**	Very High	High	Reasonable	Low	Very Low
Environmental impact	**5**	Very Low	Low	Acceptable	High	Very High

The K_i value has been developed with a broad outlook, given the fact that criteria such as the extractive processes, treatment and commercialization are taken into account so that they can be incorporated and given their proper weighting. The treatment of the proposed criteria is explained below.

2.1. Land morphology

Slopes of particular values favor the establishment of a quarry [17], since excessively plane or vertical surfaces can inhibit it. Due to this fact, this research assigns $V_i = 0$ to slopes between 35 and 55°. Increasing differences of the slope with respect to this interval, both above or below, are penalized, as it is shown in Table 3.

TABLE 3

V_i values for land morphology

Slope of the terrain (°)		V_i
0-5	85-90	4
5-15	75-85	3
15-25	65-75	2
25-35	55-65	1
35-55		0

2.2. Road and railway accesses

The existence of road and railway networks and their quality are very important aspects that must be considered before enabling a mining exploitation [18]. In both cases, their proximity eases exportation, although in the case of railway, the conditioning aspect is not the track, but the presence of a loading station.

The hierarchization of the accesses by road is considered to be of good quality ($V_i = 0$) when the outcrop is located next to a paved road or with easy access, and of bad quality ($V_i = 4$) when its location is far afield. The values $V_i = 1$, 2 and 3 are assigned to the accesses by tracks with acceptable conditions according to the seasons of the year. Table 4 shows also the V_i values for the different distances from the outcrop to the nearest railway station.

TABLE 4

V_i values for road and railway accesses

Type and quality of road accesses	V_i	Type and quality of railway accesses	V_i
Area whose distance to a road is lesser than 200 m	0	Area whose distance to a railway is lesser than 1000 m	0
Area whose distance to a road ranges between 200 and 500 m	1	Area whose distance to railway ranges between 1000 and 5000 m	1
Area whose distance to a road ranges between 500 and 1000 m	2	Area whose distance to railway ranges between 5000 and 10000 m	2
Areas which are more than 1000 m away from a road	3	Areas which are more than 10000 m away from railway	3
Difficult-to-access areas	4	Difficult-to-access areas	4

2.3. Superficial weathering and soil

The approximate weathering index is based on field estimations [19]. $V_i = 0$ is given when the fresh rock has a weathering cover with few centimeters of thickness, and $V_i = 4$ is suitable when the surface is intensely weathered, and the soil reaches thicknesses of over 3 m.

Given the difficulty to develop a macroscopic quantification of the weathering depth, it is necessary to extrapolate those depth values from adjacent areas. This fact complicates this analysis, and the actual estimation of this parameter. Table 5 quantifies the hierarchizing coefficient according to superficial weathering.

TABLE 5

V_i values for superficial weathering

Area of weathering and soil	V_i
Area without weathering and soil	0
Slightly weathered area along fractures, with <1 m of soil	1
Slightly weathered area (1-3 m), with local presence of some soil	2
Heavily weathered area (3-5 m) with soil	3
Heavily altered area (≥5 m) with continuous and thick soil	4

Contrary to previous criteria, this one does not have a spatial character and, therefore, it is hard to implement in a GIS. The different outcrops must be visited so as to assign the V_i values, according to the criteria that have been set.

2.4. Reserves

To provide an adequate treatment with GIS when assessing reserves, detailed cartography and drillholes that delimit the deposit in depth are required [20]. As the evaluation of reserves has been generally developed with observations from the surface, they are considered as inferred or estimated data, and the estimation must be necessarily qualitative. Hence, deposits are grouped as small, large, or very large, and 5 different V_i values have been set for this parameter. $V_i = 0$ is given when the reserves are very high, and $V_i = 4$ stands for very low reserves. Given the difficulty of estimating the available reserves during the previous studies, the size that the reserves must have to provide an acceptable Internal Rate of Return (IRR) is quantified. Figure 1 shows the relationship between the IRR and the reserves that are required to make exploitation of a commodity with low economic value resources sustainable [21]. A minimum extraction of 75,000 t/year would be required to achieve an acceptable IRR. If the minimum period of life set is accepted (15 years), the critical value would be fixed in 1,125,000 t. These lower reserves will be given V_i = 4, applying V_i = 0 when they are larger than 6,000,000 t. Table 6 shows the different V_i values according to the reserves.

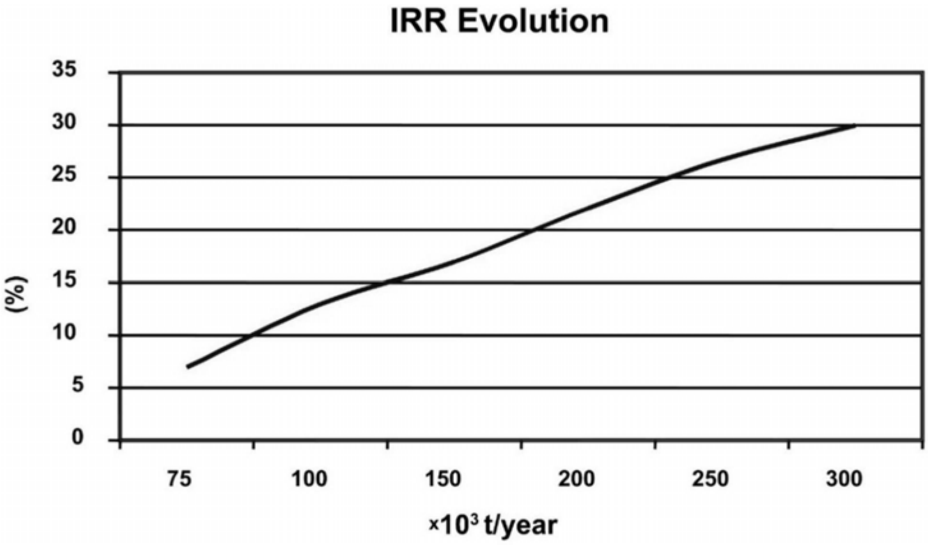

Fig. 1. IRR evolution for the different hypotheses [21]

As it happens with the previous criterion, this one is also hard to implement in GIS. For its determination, the outcrops must be visited, the reserves must be estimated as it has been described, and the V_i values must be assigned according to the criteria that have been set.

TABLE 6

V_i values for reserves

Reserves (t)	V_i
<1,125,000	**4**
1,125,000-2,500,000	**3**
2,500,000-4,000,000	**2**
4,000,000-6,000,000	**1**
>6,000,000	**0**

2.5. Enviromental impacts

One of the main criteria to assess the exploitability of a mine is the environmental impact. It is relative to the distance between the exploitation and the closer urban nuclei, which conditions acoustic pollution, dust, *etc.*, and to the visual impact [22].

Environmental impact is not very important and will receive a value $V_i = 0$ when the area lacks of legal restrictions for the enablement of a mine, and it is further than 500 m from communities or roads. Visual impact could be minimized by varying the orientation of the exploitation. $V_i = 4$ corresponds to an outcrop that is close to communities or roads, where the visual impact can be very high, or there are monuments or protected fauna and/or vegetation in its surroundings, which implies legal constraints. In addition to the previously mentioned factors, there are others, such as the proximity of a water supply or electric lines, which would impede the location of a quarry. Table 7 sets the different values for the hierarchizing coefficient according to the environmental affection of the mining exploitation.

TABLE 7

V_i values for the environmental impacts

Environmental constraints	V_i
Area that is far from communities or roads, without legal constraints	0
Area that is far from communities or roads, with legal constraints	1
Area that is close to communities or roads, without legal constraints	2
Area that is close to communities or roads, with legal constraints	3
Area that is close to communities or roads, with legal constraints and without active quarries	4

2.6. Calculation

As with the spatial criteria, whose values are obtained from GIS, and with those that are subjectively set in the field and constitute another contribution of this research, it is suggested to calculate the values for the Exploitability Index (I_e), by following a methodology that combines the proposals made by Muñoz de la Nava et al. [16], Oliveira Sousa [15] and the authors of this research.

$$I_e = \frac{\sum\left(K_i \cdot V_i\right)}{I_{\max}} \cdot 100 \tag{1}$$

Where I_e is the Exploitability Index, K_i is the Weighting Coefficient, V_i the Hierarchizing Coefficient, and $I_{\max} = 2 \cdot \sum K_i$.

With determination of the V_i values for each one of the parameters, and after applying the corresponding weighting coefficients (K_i), I_e is calculated (Eq. 1) for each outcrop. Finally, this allows for obtaining a qualitative assessment. This evaluation allows for classification of the analyzed deposits according to the factors or criteria that have been set through the I_e value of each deposit, according to the qualitative classification described in Table 8.

TABLE 8

Classification of the Exploitability Index

Total I_e value	Classification
0-20	Very Good
20-40	Good
40-60	Acceptable
60-80	Bad
80-100	Very Bad

GISs are tools that are perfectly capable of managing, combining and interpreting data that are included in one or several tables, which turns them into the ideal software for the development of multicriteria analysis. As these tools are ideally built, it is proposed that all the information is properly treated in any of the existing platforms, which allows referencing in space any results that can be obtained.

3. Results

This work presents the application of the proposed methodology to Cantabria, a Spanish region (Fig. 2) that is rich in industrial aggregates, and especially in ophites. Ophites are excellent aggregates for the production of concrete, wearing courses and specially, railway ballast.

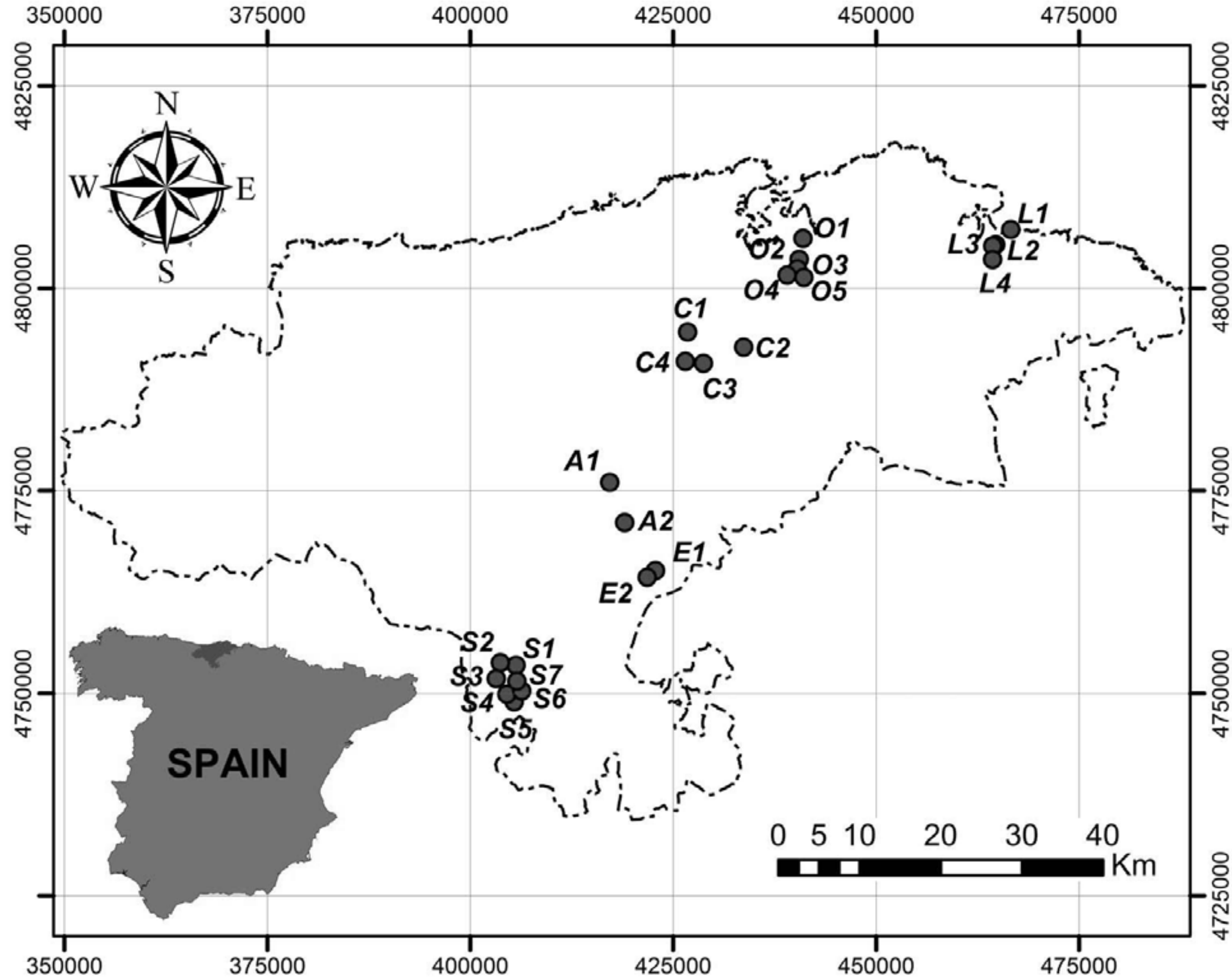

Fig. 2. Location of Cantabria (Spain), and its ophitic deposits

Given the quality and abundance of ophitic outcrops in Cantabria, they can be considered as a strategic resource for regional development. However, given their amount, prioritizing outcrops with better profitability and environmental condition is mandatory before developing exhaustive individual studies. Due to these facts, and considering a general study of all the ophitic outcrops of Cantabria, they have been grouped into six zones (Figure 2), according to proximity and similarity criteria.

Laredo: El Canto (L1), Peña Lucía (L2), Colindres (L3) and Limpias (L4).
Orejo: Orejo (O1), Solares (O2), Sobremazas (O3), Anaz (O4) and Hermosa (O5).
Central Area: San Román (C1), Esles (C2), Sandoñana (C3) and Escobedo (C4).
Alsa: Cueto Pando (A1) and Alsa Water Reservoir (A2).
Ebro: Outcrops that are close to the Ebro Water Reservoir (E1) and La Población (E2).
Southern Area: San Martín de Hoyos (S1), Olea (S2), Castrillo del Haya (S3), Rebolledo (S4), Camesa (S5), Matarrepudio (S6) and El Haya (S7).

As described above, weighting and hierarchizing coefficients have been set in the methodology for each criteria. The first two are provided by GIS tools, and the last three from field visits and the application of the established criteria. Table 9 shows these values.

TABLE 9

Hierarchizing and weighting coefficients for the outcrops

Area	Name	X UTM30	Y UTM30	Weighting					
				1	2	3	2	3	5
				Hierarchization					
				Morp.	Road Dist.	Rail. Dist.	Weath.	Reserv.	Environ. Impac.
Laredo	L1	466596	4807248	0	1	2	3	2	4
	L2	464736	4805381	0	0	1	2	2	4
	L3	464373	4805197	2	0	1	3	3	4
	L4	464370	4803527	2	0	1	3	4	4
Orejo	O1	440996	4806134	2	0	1	3	0	4
	O2	440544	4803559	2	0	0	4	3	4
	O3	440314	4802393	3	1	1	4	4	2
	O4	439051	4801610	3	1	1	3	4	2
	O5	441103	4801335	0	1	1	3	0	2
Central Area	C1	426780	4794575	2	0	1	4	0	2
	C2	433684	4792702	1	0	3	3	0	0
	C3	428748	4790714	1	0	2	3	0	2
	C4	426511	4790954	1	0	1	2	0	2
Alsa	A1	417193	4775999	2	1	1	4	0	0
	A2	419030	4771093	2	1	4	4	4	1
Ebro	E1	422833	4765166	2	0	3	3	2	4
	E2	421818	4764334	2	0	3	3	3	4
Southern Area	S1	405647	4753471	2	2	2	2	0	0
	S2	403719	4753778	1	1	2	2	0	1
	S3	403213	4751824	2	0	1	1	2	0
	S4	405430	4748928	1	1	1	2	4	1
	S5	404522	4749890	1	1	1	2	4	1
	S6	406357	4750296	2	1	0	1	2	0
	S7	405756	4751498	2	1	1	2	2	4

After that, partial exploitability indexes have been calculated for each criteria in all the outcrops. The sum of these indexes provides the Total Exploitability Index (Total I_e) for each outcrop, which can be applied for the final classification (Table 10).

TABLE 10

Total Exploitability Index for the different outcrops

AREA	Outcrop	Mor-phology	Road accesses	Railway Accesses	Weath-ering	Reserves	Environ-mental Impact	Total I_e	Total Assessment
Laredo	L1	0.00	3.12	9.37	9.37	9.37	31.25	62.48	**Bad**
	L2	0.00	0.00	4.69	6.25	9.37	31.25	51.56	**Acceptable**
	L3	3.12	0.00	4.69	9.37	14.06	31.25	62.49	**Bad**
	L4	3.12	0.00	4.69	9.37	18.75	31.25	67.18	**Bad**
Orejo	O1	3.12	0.00	4.69	9.37	0.00	31.25	48.42	**Acceptable**
	O2	3.12	0.00	0.00	12.50	14.06	31.25	60.93	**Bad**
	O3	4.69	3.12	4.69	12.50	18.75	15.62	59.37	**Acceptable**
	O4	4.69	3.12	4.69	9.37	18.75	15.62	56.24	**Acceptable**
	O5	0.00	3.12	4.69	9.37	0.00	15.62	32.80	**Good**
Central	C1	3.12	0.00	4.69	12.50	0.00	15.62	35.93	**Good**
	C2	1.56	0.00	14.00	9.37	0.00	0.00	24.99	**Good**
	C3	1.56	0.00	9.37	9.37	0.00	15.62	35.93	**Good**
	C4	1.56	0.00	4.69	6.25	0.00	15.62	28.12	**Good**
Alsa	A1	3.12	3.12	4.69	12.50	0.00	0.00	23.43	**Good**
	A2	3.12	3.12	18.70	12.50	18.75	7.81	64.05	**Bad**
Ebro	E1	3.12	0.00	14.06	9.37	9.37	31.25	67.17	**Bad**
	E2	3.12	0.00	14.00	9.37	14.06	31.25	71.86	**Bad**
Southern Area	S1	3.12	6.25	9.37	6.25	0.00	0.00	24.99	**Good**
	S2	1.56	3.12	9.37	6.25	0.00	7.81	28.11	**Good**
	S3	3.12	0.00	4.69	3.12	9.37	0.00	20.30	**Good**
	S4	1.56	3.12	4.69	6.25	18.75	7.81	42.18	**Acceptable**
	S5	1.56	3.12	4.69	6.25	18.75	7.81	42.18	**Acceptable**
	S6	3.12	3.12	0.00	3.12	9.37	0.00	18.73	**Very Good**
	S7	3.12	3.12	4.69	6.25	9.37	31.25	57.80	**Acceptable**

The results can be linked to the territory analyzed and can be visualized in a thematic cartography that has been purposely designed, thanks to the powerful GIS tools for the generation of graphic outputs, as is shown in Figure 3.

The use of GIS tools as the most suitable alternative for multicriteria analysis is not subject to discussion. GIS tools have become essential instruments for this type of analysis and the subsequent decision-making, with the advantage of allowing the referencing of these analysis with respect to space, as it is shown in this research. However, the selection of the most suitable platform, or the one with a better-implemented module for multicriteria analyses is another issue. Nowadays, this module is perfectly implemented in most platforms, either commercial or free.

The experiment that has been developed to apply the methodology largely suits its main aim: the possibility to determine the Exploitability Index of several outcrops by the application

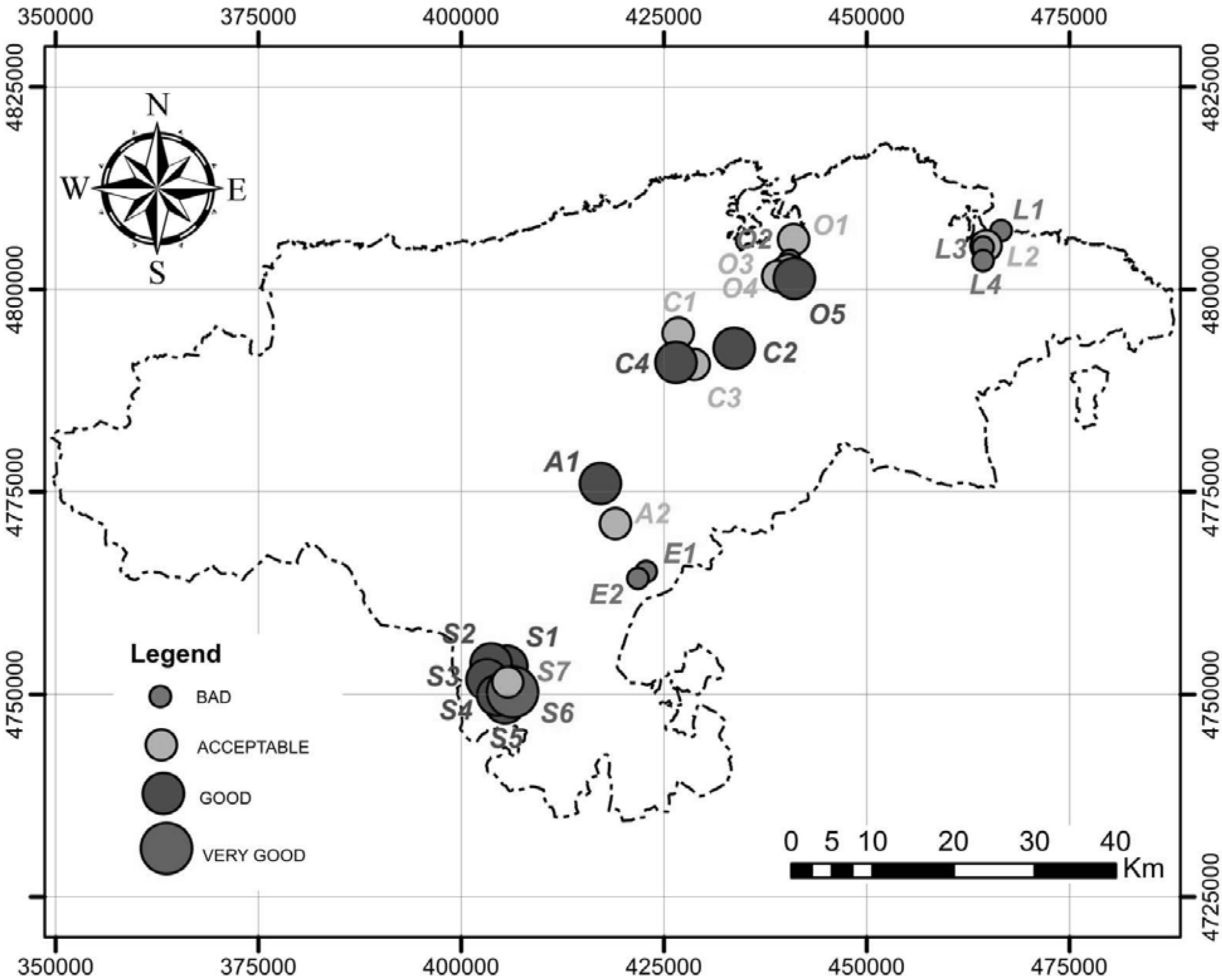

Fig. 3. Final classification of the Exploitability Index of the ophitic outcrops in Cantabria

of a series of criteria and certain weighting/hierarchization, and to classify their suitability for exploitation in a qualitative way. A different matter is the application of this methodology here to a very specific type of industrial aggregate. It could be equally well applied to other kind of aggregates, but the criteria could be expanded.

The criteria result from the combination of other authors' recommendations and the experience gathered during the development of this research. Although they have been analyzed and weighted with objective criteria, with the consideration of almost all the potential effects that the development of a mining site implies, other criteria or weights could be considered, according to the type of aggregate. A good analysis requires a good criteria study and the use of the same criteria for all the outcrops, given that the comparison of the results of each outcrop removes any potential bad hierarchization if they are equally applied for each outcrop.

The evaluation of the results of this research, whose finding is so innovative, is challenging to articulate. To assess the method, it can be checked that the only deposit that counts with a "very good" evaluation of its Exploitability Index, Outcrop S6 (Matarrepudio, Southern Area), is the only outcrop that was exploited among all the considered deposits. Another possibly would be the contrast of the results of this research with other alternatives for the evaluation of outcrops, although it is hard to find another methodology that considers as many criteria as this one.

Other new lines of enquiry arise from this research, which are mainly focused on determining the importance of other dismissed criteria due to their scarce influence. The application of other hierarchization or weightings can be another line of research, along with the application of this methodology to other types of aggregates, for which the set of criteria could be extrapolated.

4. Conclusions

As a result of this research, an Exploitability Index has been obtained by the application of multicriteria analysis with GIS tools. It has produced a logic/rational criterion to hierarchize the outcrops of industrial aggregates when choosing which are suitable for exploitation or not, as supported by the results obtained.

The criteria that have been applied for the determination of the Exploitability Index are derived from a combination of the proposals made by other authors and the experience that has been acquired during the development of this research. The selection of the criteria applied to the datasets is another contribution of this research. The criteria that have been chosen are land morphology, road and railway accesses, grade of superficial weathering or soil, reserves and, finally, environmental impact.

Hierarchizing and weighting of criteria are the final steps to determine the Exploitability Index of each outcrop. The hierarchizing and weighting coefficients are adopted in a justified way, according to the works developed by other authors, and the experience gathered during this research. Various criteria of differing nature have been used. The process to hierarchize and weight the criteria is the third contribution of this research. It provides flexibility as the main advantage, as it allows for the adjustment of the importance of each criterion, modifying the intervals of the different classes to achieve certain specific goals, and updating the Exploitability Indexes when new data are available.

Multicriteria analysis have been applied in many fields of mining, but they had never been used for the determination of an Exploitability Index before. This Index provides a decision-making tool to choose the outcrop that offers the best possibilities to be exploited from a mining point of view. This is the main contribution of this research, that has been properly tested and contrasted, which implies a scientific evidence of the proposed method.

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