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Original Article

The use of multi-criteria analysis in the recovery of abandoned mines: a study of intervention in Portugal

A utilização de análise multicritério na recuperação de minas abandonadas: estudo da intervenção em Portugal

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Abstract

Considering that the budget for the recovery of abandoned mining zones is limited, it was necessary to develop a model that would make it possible to choose which mines should be targeted for intervention, taking into account the various factors by which their external effects may be assessed (the environment, public health, the landscape and their usefulness to industrial archaeology). A multi-criteria analysis using the analytic hierarchy process, in which each major factor, result, and mine are compared, was employed to generate an innovative assessment model that guaranteed that the overall value of the intervention was maximised, compared to two other methods (intervention ranked by the greatest overall severity and ranked by the cost–benefit ratio). The results indicate an economically and socially viable and efficient choice, making it possible to undertake new similar studies.

Keywords: Brownfields; Multi-criteria analysis; Analytic hierarchy process (AHP); Capital rationing decision

Resumo

Tendo em consideração a existência de uma limitação orçamentária que inviabilizava a recuperação de todas as áreas mineiras abandonadas, foi necessário desenvolver um modelo que permitisse escolher quais as minas que seriam objeto de intervenção, tendo em consideração os diferentes fatores de avaliação de seus efeitos externos (no ambiente, na saúde pública, na paisagem e no seu aproveitamento para a arqueologia industrial). A partir de uma análise multicritério (utilizando o *Analytical Hierarchy Process* - AHP), onde cada fator preponderante, resultado e mina foram comparados, gerou-se um modelo inovador de avaliação onde se garantiu a maximização do valor global da intervenção, em comparação a outros dois métodos (intervenção ordenada pela maior gravidade global e pela relação custo-benefício). Os resultados apontam para uma escolha econômica e socialmente viável e eficiente, permitindo instigar novos estudos análogos.

Palavras-chave: Minas abandonadas (brownfields); Análise multicritério; *Analytical Hierarchy Process* (AHP); Decisões com restrição orçamentária

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Introduction

The recovery of abandoned mines is essential from a social perspective, given their visibly negative effects, predominantly due to the water pollution, soil contamination, and inadequately protected landfills associated with these mines (Abreu, Matias, Magellan, & Basto, 2008; Antunes & Albuquerque, 2013; Cesar, Egler, Polivanov, Castilhos, & Rodrigues, 2011, Mayan, Silva, & Begonha, 2006; Neves & Matias, 2008; Veiga & Hinton, 2002). The complexity of the effects, which include multiple dimensions, has been the object of several scientific developments, particularly multi-criteria analysis (Huang, Keisler, & Linkov, 2011; Pizzol et al., 2016; Wedding & Crawford-Brown, 2007).

What criteria should guide the choice of which mines to recover? How should the investment in mine recovery be allocated, considering budgetary restrictions? The present article seeks to present an innovative approach to selecting which mines should be recovered based on a study conducted in Portugal. Given the high number of abandoned mines in that country and the limited budget for their recovery, it was necessary to identify priority mines, considering the set of harmful effects to be mitigated and the cost of each project.

The theoretical justification for this study is that it addresses a problem of project selection in a context of capital rationing (Weingartner, 1963, 1977), raising the issue of the various harmful effects identified, to find a single indicator of "value" for each mine (defined, in this case, as the amount of harm to be eliminated). Given that some of the harmful effects are difficult to quantify, it was necessary to use an analysis that compares the mines being studied and, in this manner, creates an index for each mine. To that end, a multi-criteria analysis model was applied.

The hierarchy model chosen was the analytic hierarchy process (AHP), developed by Saaty (1980, 1986), which, in a multi-criteria and hierarchical structure, enables the endogenous generation of weights that reflect the value associated with recovery so that these are not assigned arbitrarily; simultaneously, it tests the consistency of the values assigned by evaluators. These weights were then used as coefficients of the objective function to be maximised in the model for selecting projects in a context of capital rationing.

This paper also aims to contribute to a broad understanding of the model by which abandoned mines are analysed and selected for recovery, using a socioeconomic perspective that may be applied to other similar interventions.

In addition to this introduction, which presents the problem, objective, and justifications, this study has five other sections. The second addresses the theoretical framework. The third describes the research environment surrounding the study's problem and motivations. The fourth addresses the methodology used to develop the proposed model, and the fifth contains the findings and discussions arising from the research conducted. Finally, the sixth chapter covers the conclusions, followed by the references.

Multi-criteria analysis

The initial studies on choice or selection analysis took into account only one objective function. The perception that a single function was insufficient to simulate real-world situations led operational research to study multiple conditions and selection criteria. This led to the need to use multi-criteria analysis, which may be viewed as a method of allowing the manager to make choices in situations of ambiguity, bifurcations, and uncertainties (Roy & Bouyssou, 1991).

According to Parreiras (2006), there are two schools of multi-criteria analysis: an American school and a French or European school. The American school methods focus the decision on the construction of a utility function, whereas the French school treats the decision as a two-stage process, in which the first stage consists of comparison and the second stage explores relations according to guidelines or classifications. In other words, the first school can be classified as normative and the second as constructivist, in that it helps the manager construct his or her preferences (Parreiras, 2006). Some authors thus differentiate between the American school methods, as multiple criteria decision making (MCDM), and the French School methods, as multi-criteria decision aid (MCDA) (Parreiras, 2006; Roy, 1990; Vincke, 1986), although other authors make no distinction between these two frameworks.

One of the most well-known and frequently used methods of multi-criteria analysis (Wallenius et al., 2008) is the AHP method developed by Saaty (1980, 1986), which structures the decision process by identifying an overall objective, criteria, and alternatives. It is a versatile method that has had various applications, including the allocation of energy for industries, transportation planning, the process of evaluating candidates for election, and the choice of priorities for promoting teachers and researchers, among others (eg. Horn, 1997; Huang et al., 2008; Liberatore and Nydick, 2008; Sipahi and Timor, 2010; Wong and Li, 2008; Zavadskas et al., 2014). Its theoretical features and robust applicability justify its choice for the analysis of mines to be recovered in Portugal.

The AHP is based on three basic principles (Saaty, 1986, 2000), which constitute the three stages of the process:

1. The principle of decomposition consists of breaking down complex problems into less complex "sub-problems" so that humans, with their cognitive constraints, are better able to analyse and decide upon them. Hierarchical decomposition is even considered by Simon (1960) to be the best method for humans to address complexity; therefore, the first step of the AHP is to precisely break down the problem into a hierarchical decision model, including criteria, sub-criteria, and alternatives.
2. The principle of comparative judgement holds that humans are capable of drawing comparisons only within a limited spectrum of alternatives, as demonstrated by various experiments and studies on brain functioning. Hence, instead of

attempting to arbitrarily and simultaneously assign weights to every criterion or classification in all alternatives, it is preferable to make pairwise comparative judgements of criteria or alternatives. Although these comparisons are subjective ("equally important," "somewhat more important," "much more important," "very much more important," and "extremely more important"), they are performed on a scale within the human capacity to draw comparisons (1, 3, 5, 7, and 9).
3. The principle of hierarchical composition consists of appropriately aggregating the values determined for each alternative for each criterion and sub-criterion, based on the respective weightings of these criteria and sub-criteria, until a final "ranking" of each alternative is obtained.

The AHP employs comparisons between alternatives (preferably performed by a panel of specialists), measuring these preferences through the use of scales (Saaty, 1980, 1986), with the traditional AHP scale of relative importance consisting of nine levels (Table 1).

Mathematically, according to Zambon, Carneiro, Silva, and Negri (2005), the AHP method consists of generating an $n \times n$ square matrix, in which the rows and columns correspond to the criteria analysed for the problem at hand, with the a_{ij} value corresponding to the relative importance of the criteria in row i compared to the criteria in row j. According to the same authors, because this matrix is reciprocal, only the lower half the triangle must be evaluated, given that the other half derives from it and the main diagonal is equal to 1.

Research environment

In Portugal, the state has established goals for the environmental recovery of areas affected by the activity of now-abandoned mines for the public entity in charge of the operation (EXMIN – Companhia de Indústria e Serviços Mineiros e Ambientais SA, later integrated into the EDM – Empresa de Desenvolvimento Mineiro SA). These goals were (DL No. 198-A/2001, Art 3):

1. To eliminate, in a long-lasting manner, the risks to public health and safety resulting from water pollution, soil contamination, and the possible existence of unstable tailings or unsecured shafts;
2. To restore the surrounding landscape to natural conditions that support local flora and fauna in a state similar to their respective habitats prior to mining activities;
3. To ensure the preservation of the patrimony left by the former mines, wherever these are important to the economy or industrial archaeology; and
4. To promote the economic, cultural, and scientific value of the recovered areas, as appropriate to each case, whether it be for agriculture, forestry, tourism, or cultural use.

Thus, it can be observed that, conceptually, these objectives raised issues that are problematic for their implementation, namely:

- The identification of the various criteria by which the damage caused by abandoned mines should be assessed (because there were references to public health, pollution, the landscape, etc.);
- The weighting of the various criteria because these distinct concerns will influence the final decision;
- Whether damage will be estimated in absolute terms or by ranking the mines and judging the relative benefits to be gained from the recovery of each mine, compared to other mines; and
- The choice of the best combination/set of interventions in the mines, in a manner that maximises the benefit of these interventions.

It is important to emphasise that Portugal's limited financial resources will not cover the cost of recovering all mines, making it necessary to choose which mines will be recovered, taking into account the available budget and other technical limitations.

Conceptually, this is a problem of multi-criteria decision-making, for which the AHP methodology is suited (for a survey, see Ishizaka & Labib, 2009, 2011; Mardani et al., 2015; Roy & Słowiński, 2013), in that it allows complex decisions to be modelled in a hierarchical structure of criteria, sub-criteria, and alternatives, ranking these alternatives and assigning weights to the criteria and sub-criteria defined.

This methodology has been applied in various areas of business management, such as the location of business projects (e.g., Yang, & Lee, 1997), the establishment of organisational goals (for companies, non-profits, etc.; see Cheng & Li, 2001; Crowe, Noble, & Machimada, 1998, Hafeez, Zhang, & Malak, 2002), and the choice of technological options (e.g., see the articles by Oztaysi, 2014; Tam & Tummala, 2001)

Table 1
Relative importance.

Intensity of the relative importance	Importance	Explanation
1	Equally important	Two activities contribute equally to the objective
3	Somewhat more important	Experience and judgement slightly favour one criterion over another
5	Much more important	Experience and judgement strongly favour one criterion over another
7	Very much more important	Experience and judgement show that one of the criteria is more important to the objective.
9	Extremely more important	There is evidence that one criterion is strongly predominant over the other.
2, 4, 6, and 8	Intermediate	Can also be used if necessary.

Source: Adapted from Saaty (1986, p. 843).

or investments (Aragonés-Beltrán, Chaparro-González, Pastor-Ferrando, & Pla-Rubio, 2014; García et al., 2014; Yavuz, 2015).

Specifically in the environmental field, in which multi-criteria methodologies are considered relevant (Calizaya, Meixner, Bengtsson, & Berndtsson, 2010; Wang, Jing, Zhang, & Zhao, 2009), the AHP methodology has been employed in multiple contexts (e.g., Baby, 2013; Chatzimouratidis & Pilavachi, 2009; Ismail & Abdullah, 2012; Kaya & Kahraman, 2010; Schmoldt & Peterson, 2000; Shen, Muduli, & Barve, 2015; Solnes, 2003).

As noted above, according to Zahedi (1986), in the field of "comparative judgements," comparisons are drawn between each pair of alternatives. These comparisons make it possible to build matrices (one for each criterion or sub-criterion) from which the relative positioning of each alternative for the criterion in question can be inferred. Based on the answers of the experts who analysed each alternative's contribution to the objective, assuming that the implicit ranking of each alternative i is given by w_i, a comparison of alternative i with alternative j gives a value for the ratio between w_i and w_j, thus building a square matrix whose size is equal to the number of alternatives and whose main diagonal we can designate as A:

$$A = \begin{bmatrix} 1 & w_1/w_2 & \cdots & w_1/w_j & \cdots & w_1/w_n \\ w_2/w_1 & 1 & \cdots & w_2/w_j & \cdots & \cdots \\ \cdots & \cdots & 1 & \cdots & \cdots & \cdots \\ w_i/w_1 & \cdots & \cdots & w_i/w_j & \cdots & w_i/w_n \\ \cdots & \cdots & \cdots & \cdots & 1 & \cdots \\ w_n/w_1 & \cdots & \cdots & \cdots & \cdots & 1 \end{bmatrix}$$

Considering the vector column W (w_1, …, w_i, …, w_n) to be the final contribution (still unknown) of each alternative to the objective, the multiplication of A by W (matrix dimension ($n \times n$) and ($n \times 1$)) yields the matrix nW. From the equation $A \times W = nW$, one can estimate W (from the matrix's own value). This determines the "ranking" of each alternative on a standardised scale in which $\sum_{i=1}^{n} W_i = 1$. The same applies to the weights of the criteria and sub-criteria (for a more thorough discussion of the mathematical aspects, see Zahedi (1986)).

The use of this methodology made it possible to resolve the problem of mine ranking using a multi-criteria approach. The subjective nature of this methodology (Cheng & Li, 2001) requires the cooperation of technicians who are qualified to compare the alternatives for each type of criterion, which reduces subjectivity. Simultaneously, as an innovative method of supplying missing information, making the process easier and partially limiting arbitrariness, homogeneous groups of mines were created within each criterion; these were used as the units of comparison, thereby avoiding the need for an extremely detailed and possibly erroneous comparison of every mine with every other mine.

Having resolved the question of how to rank mines according to their contribution to an objective (such as environmental restoration or the protection of public health), the second problem was to identify which mines should be selected to maximise the contribution to the objective within the available budget. Mathematically, the model in question followed a simplified version of Weingarten's form (1963, 1977):

$$\text{Max } V = \alpha_{1P_1} + \alpha_{2P_2} + \cdots + \alpha_{npn}$$

$$s \cdot a \cdot P_i = 0 \quad \text{or} \quad 1 \quad (i = 1, \ldots, n)$$

$$C_1 P_1 + C_2 P_2 + \cdots + C_n P_n \le D$$

where:

- P_i is the project, which is assigned a value of either 1 or 0, signifying that it is selected or eliminated;
- α_i is the weight assigned to project i, drawn from the results of the AHP;
- C_i is the estimated cost for project i (hypothetically, the current value of this cost for period 0); and
- D is the total amount budgeted for the recovery of abandoned mines.

The next section addresses how the methods involved were comparatively analysed.

Methodology – proposed hierarchy model

This research is a field study that sought to compare the results from the application of other models with the proposed model to determine whether the model developed is an alternative to previously existing models from a socioeconomic perspective in a context of limited resources.

After selecting the projects that maximise the overall contribution to certain objectives within the available budget, in view of their relative value in attaining the desired objectives and the cost of attaining those objectives, this study sought to operationalise the model, including additional limitations related to problems of precedence, incompatibility, and the joint implementation of multiple projects.

The multidimensional characteristics of the analysis undertaken, involving different types of mines (radioactive, polymetallic sulphide deposits, and others) and different effects (environmental, public health, and others), called for analytical and decision-making meetings with a diverse group of participants. To that end, specialists in different mine types, regions, and analytical approaches were chosen in accordance with the recommendations of McCarthy (2002) and White and Bourne (2007).

Given the multiple objectives described, four initial concerns were identified: the resolution of environmental problems; the resolution of safety and public health problems; the resolution of landscape problems; and the exploitation of existing and potentially useful environmental, industrial, and archaeological patrimony.

The direct results of intervention in a mine were considered to involve cleaning up polluted water, soil, and air; safety; the surrounding landscape; and the valorisation of patrimony. It was considered that these would make it possible to respond indirectly to the four sets of concerns. Thus, the problem was

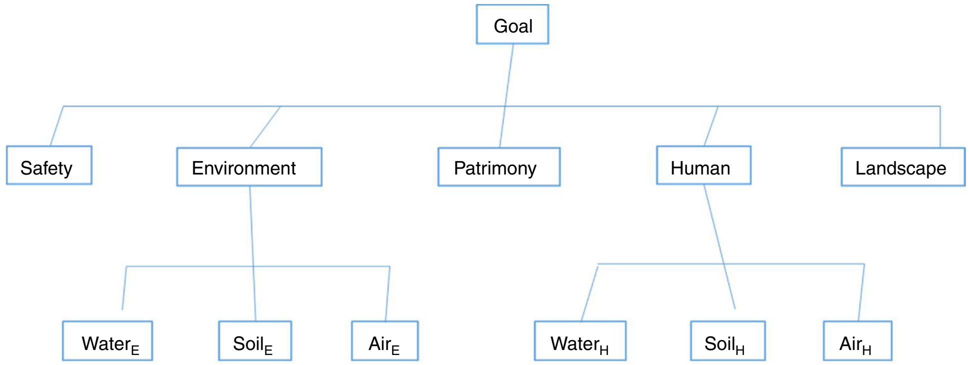

Fig. 1. Structure of the multi-criteria analytical model.
Source: Research data.

modelled to clarify the process of hierarchisation, considering five final objectives:

1. Resolution of the environmental problem (designated as Environment);
2. Resolution of the problem of public health and the human use of resources (designated as Human);
3. Resolution of the public safety problem (designated as Safety);
4. Resolution of the landscape problem (designated as Landscape)
5. Exploitation of the environmental, industrial, and archaeological patrimony (designated as Patrimony).

The criteria by which each mine was ranked were based on how each project contributed to each of the objectives as follows:

1. The *Environmental objective* depends on the results of the mine intervention on water, soil, and air pollution, which, in turn, result from the combination of the intervention's impacts on the physical and chemical factors with the environmental value of the affected ecosystems. We therefore have three criteria that contribute to this objective:
   - The contribution of the water clean-up to the Environmental objective ($WATER_E$);
   - The contribution of the soil clean-up to the Environmental objective ($SOIL_E$); and
   - The contribution of the air clean-up to the Environmental objective (AIR_E).
2. In addition to the results of the water and soil clean-up, the *Human objective* depends on the results of air clean-up (in the case of atmospheric pollution from radioactivity and radon gas). As with the previous case, these results depend on not only the related physical and chemical parameters but also their combination with the presence of human populations or activity (such as agriculture) in the affected zone. Thus, we have three criteria that contribute to this objective:
   - The contribution of water clean-up to the Human objective ($WATER_H$);
   - The contribution of soil clean-up to the Human objective ($SOIL_H$); and
   - The contribution of air clean-up to the Human objective (AIR_H).
3. The *Safety objective* depends on a single result, the intervention's impact on public safety, which naturally involves not only the structural stability of landfills or the sealing of shafts but also the human use of the site. A single criterion is relevant here: "the mine intervention's contribution to the Safety objective."
4. The *Landscape objective* is similar to the Safety objective, insofar as it depends on a single result: the intervention's impact on the landscape due to the removal of tailings and the disposal of waste and ruins. There is thus only one criterion that contributes to this objective: "the mine intervention's contribution to the Landscape objective."
5. Finally, the *Patrimony objective* also depends only on the intervention's impact on the potential recovery of the environmental, industrial, and archaeological patrimony in the vicinity of the mine, including conditions that favour access, recovery, and increasing the value of the patrimony as a result of intervention. The final criterion, then, is "the mine intervention's contribution to the Patrimony objective."

Given these objectives, the structure of the analytical model is shown in Fig. 1.

Based on this model (Fig. 1), conceptually, all intervention projects would have to be compared pairwise for each of the nine criteria: their contribution to the Environmental objective through polluted water clean-up; their contribution to the Environmental objective through soil clean-up; their contribution to the Human objective through polluted water clean-up; and so on. Based on the available data, the data for supporting the evaluation of projects by each of the nine criteria could be grouped as shown in Fig. 2.

The entity commissioned for the project (EXMIN) provided a form describing each of the 172 mines; this form served as the basis for an initial screening based on two exclusion criteria to identify the candidates for more detailed consideration and possible intervention. In this manner, the group of candidates

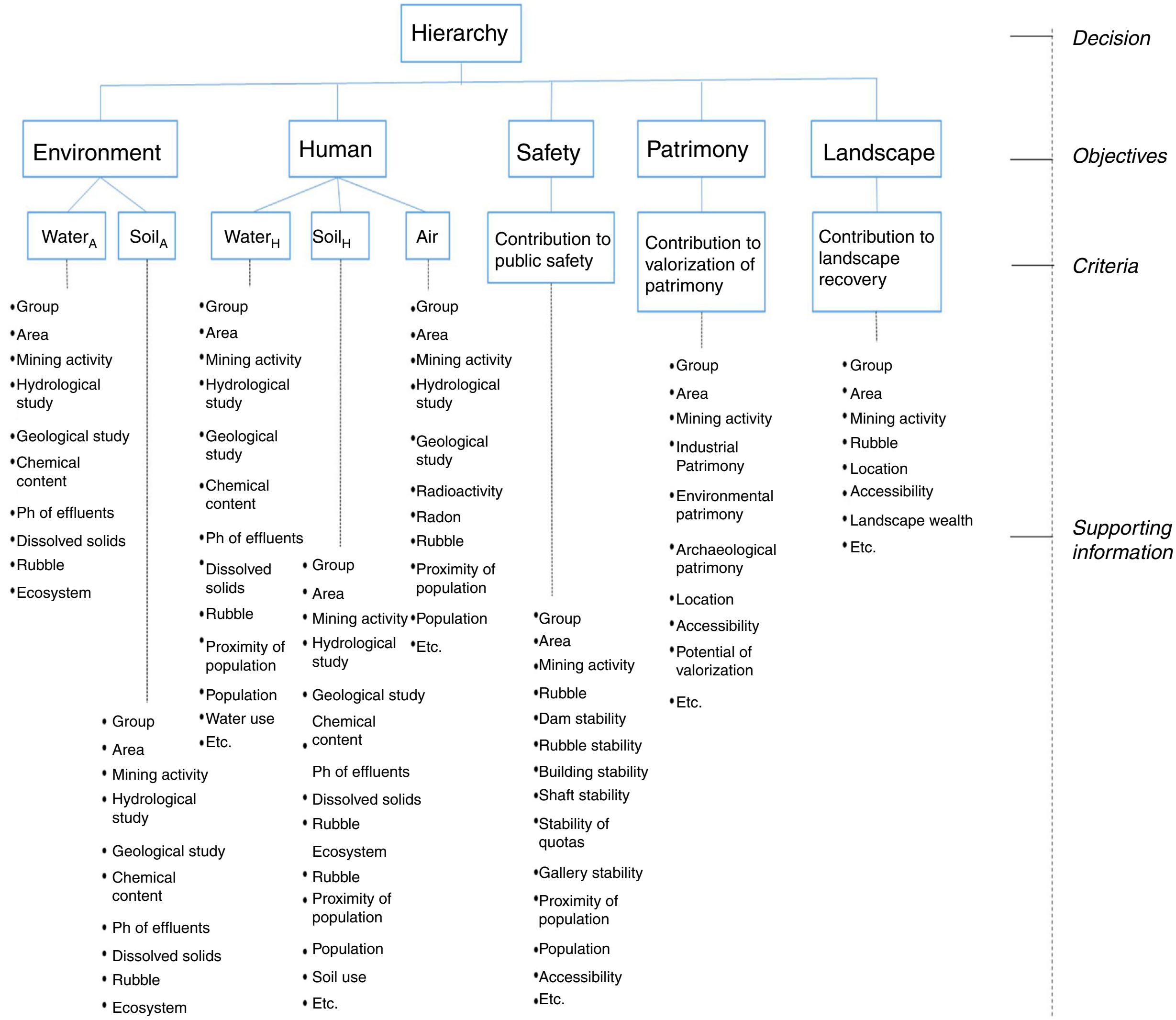

Fig. 2. Hierarchy model and supporting data.
Source: Research data.

was narrowed to 60 mines, which were subjected to the AHP model.

The exclusion criteria were the following:

- Mines that posed no safety risk or pollution effects on the population, soil, or water were eliminated;
- Mines were also eliminated in the pre-screening process if the impact on soil, water, or public safety was deemed negligible due to the presence of several factors, such as the small size of the mine, the absence of major pollutants, or being located in an inaccessible or sparsely populated area.

Cut-off criteria were also used in the screening to focus the analysis on the most important mines, designated in Table 2 as the "pre-selected mines."

To draw the comparisons among these 60 pre-selected mines according to each of the nine criteria in a timely manner and, in particular, to limit inconsistencies in the comparisons, five classes were defined for each of the criteria so that mines with similar characteristics were grouped together; each of the 60 pre-selected mines was then ranked using this process.

The various criteria were also compared pairwise within the same group using the following ranking, which was arrived at after much debate. (The terms used for comparison are the following: "equally important," "somewhat more important," "much more important," "very much more important," and "extremely more important," corresponding to a numerical scale of "1," "3," "5," "7," and "9," respectively):

Environment:

- Water "much more important" than Soil;
- Water "extremely more important" than Air;
- Soil "much more important" than Air.

Human:

- Water "somewhat more important" than Soil;
- Water "much more important" than Air;
- Soil "somewhat more important" than Air.

Table 2
List of mines.

Criterion	Mines	No.
No impact	Martinho de Angueira, Moncorvo, Beça, Tapada do Lobo n° 2, Lagares – Rebentão, Ordes, Vieiros, Regoufe, Bejanca, Cume, Palhal, Escádia Grande, França, Alto do Sião, Três Minas, Poço das Freitas, Costas do Marão, Banjas, S. Pedro da Cova, Saramaga, Cabecinho de Martinel, Horta da Reveza (Mina de Bancanes), Monte dos Mestre, Algaré, Herdade da Juliana, Lagoas do Paço, Alcaria Queimada, Ferrarias (Covas dos Mouros), Cortes Pereiras, Tapada dos Mercados, Sentinela, Fontainha-Gradiz, Vale da Videira, Vale do Tamão, Sevilha, Luz, Quinta das Seixas, Cótimos, A. do Cavalo, Freixinho, Fontinha, Eira do Brejo, and Alto da Rasa	74
Negligible impact	Pinheiro, Várzea, Herdade da Tinoca, Herdade da Mostardeira, Bugalho, Miguel Vacas, Arado do Castanheiro, Alvito, Aparis, Caeirinha, Gourim, Talhadas, Pintor, Corguinha e Prazos, Barroca Funda, Tentinolho, Carril, Pedreiros, Coitos, Ervideira, Ribeira do Ferro, Corga de Valbom, Valdante, Mortórios, Prado Velho, Póvoa de Cervães, Chaminé, Couto Mineiro do Pejão (minas do Pejão e Germunde), Formiga, Lenteiros, Vale Côvo, and Herdade da Caeira	33
No information	Grou, Serra da Bofeta, and Carris	3
Pre-selected mines	Fernando, Barrôco I, Borralha, Canto do Lagar, Carrasca, Ceife, Vale das Gatas, Chança, Cruz da Faia, Ferreiros, Fonte Velho, Mata da Rainha, Mondego Sul, Orada, Pera do Moço, Pinhal do Souto, Reboleiro, Ribeira, Ribeira do Bôco, Rosmaneira, S.D. Moreira de Rei, Tuela, Urgeiriça, Agrup. A (Talhadas/Coval da Mó/Braçal/Malhada), Agrup. B (Herd. do Montinho/Barrigão/Ferragudo), and Agrup. C (Cercal/Rosalgar)	60

Source: Research data.

Overall Objective:

- Environment and Human "equally important";
- Environment "somewhat more important" than Safety;
- Environment "very much more important" than Landscape;
- Environment "extremely more important" than Patrimony;
- Safety "much more important" than Landscape;
- Landscape "somewhat more important" than Patrimony.

The proposed model makes it possible to address the matter in a technically well-grounded manner and to present workable solutions, in that:

(i) It allows for the combination of multiple objectives that are evaluated (in relative and absolute terms) according to various criteria;
(ii) It makes it possible to decompose a complex, systemic problem into its various components, hierarchically defined;
(iii) It is based on comparing mines (or groups of mines) in a manner that makes it possible to define the relative importance of each attribute of a mine (or group of mines) compared to another mine (or group of mines); and
(iv) It makes it possible to limit any inconsistencies in the comparisons by exploiting computational software that can calculate an index of inconsistency.

This model made it possible to generate a quantitative score for the importance of the EXMIN intervention in each mine compared to each of the other 59 mines according to each of the nine evaluation criteria, with the overall benefit of intervention in a particular mine being the weighted sum of the benefits identified for that mine using each of the nine criteria.

Once each mine had been ranked in terms of the intervention objectives using these nine criteria, the methodology was able to generate an intervention plan (that is, a list showing the overall benefit of intervention associated with each mine), which was then weighted according to the cost associated with each intervention. The following section covers the main results and discussion of this study.

Results and discussion

Using pairwise comparisons of the investment criteria and sub-criteria set by the panel of experts, the AHP (through the use of the Expert Choice© software) yielded the following endogenously assigned weightings:

- Landscape – 0.055;
- Human – 0.37, with sub-criteria:
  - Air – 0.105;
  - Water – 0.637;
  - Soil – 0.258;
- Environment – 0.37, composed of the following sub-criteria:
  - Air – 0.058;
  - Water – 0.735;
  - Soil – 0.207;
- Safety – 0.175;
- Patrimony – 0.03

By multiplying the "score" given by the model to each mine in each of the sub-criteria using these weights, it was possible to arrive at an overall value of each mine, as shown in Table 3. These were the coefficients assigned to each mine in the objective function, representing the benefit of recovering that mine.

Once the overall value of recovering each mine has been determined, it is important to bear in mind that the main objec-

Table 3
Overall value for each mine.

Urgeiriça .0548	Vale das Gatas .0147	Ribeira .0086
Aljustrel .0505	Borralha .0144	Freixeda .0084
São Domingos .0465	H. Gouv. de Baixo .0142	Picoto .0084
Covas .0441	Ribeira do Bôco .0142	Cruz da Faia .0084
C. Baixa .0412	Terramonte .0137	Adória .0083
Bica .0394	Vales .0137	Espinho .0075
Q. do Bispo .0382	Tuela .0136	Barrôco I .0071
Lousal .0347	Chanca .0136	S.D. Moreira de Rei 0071
S. da Caveira .0322	Rosmaneira .0134	Pousadela .0070
S.ª das Fontes .0322	Jales .0131	Barrôco D. Frango .0070
Argozelo .0289	Mata da Rainha .0123	Mestras .0068
Montesinho .0274	Castelejo .0119	Rio de Frades .0067
V. da Abrutiga .0234	Alto da Várzea .0105	Agrupamento A .0067
Mondego Sul .0234	Carrasca .0104	Orada 0064
Ferreiros .0217	Agrupamento C .0102	Canto do Lagar .0063
Vale D'Arca .0184	Pinhal do Souto .0101	Pera do Moço .0061
Santo António .0182	Reboleiro .0098	Agrupamento B .0060
Fonte Santa .0167	Freixiosa .0091	Azenhas .0053
A. Fab. Barracão .0150	Forte Velho .0087	Ceife 0051
Murçós .0148	Maria Dónis .0087	Chãs .0045

Source: Research data.

tive is to select abandoned mines for intervention in the context of budgetary restrictions (which are assumed to apply to a single period). Basically, this means combining the preferential ranking of interventions based on each intervention's relative "utility" with the constraint that resources are insufficient to undertake all simultaneously, bearing in mind the indivisibility of each project (in fact, the interventions in the Urgeiriça, Aljustrel, São Domingos, and Serra da Caveira mines were divided into several sub-projects). Consequently, the selected interventions were those that, within the budgetary constraints for each period, maximise an objective function whose coefficients were endogenously established through a model that addresses the choices made for the criteria chosen for comparing the mines (the AHP model).

The results of three alternatives choices for the mines to be targeted for intervention are shown here:

- The selection of projects based on the severity of each mine's situation, that is, based on the absolute contribution to the objective, given the parameters shown in Table 2 (which appears to be the criteria most frequently used by agents in this field) would result in attaining a much smaller part of the objective (Scenario A);
- The selection of projects based on not only their absolute contribution to the objective but also cost considerations, thus prioritising interventions with higher cost–benefit ratios (Scenario B); and
- The maximisation of the objective function through the AHP (considering the degree of severity of each mine), taking into account budgetary constraints, using linear programming techniques (Scenario C).

In this last solution, the selection of projects resulting from the resolution of the entire linear optimisation problem, subject to budgetary constraints, will reflect the combination of two factors:

- On one hand, the selection of projects is made in descending order of the resources used compared to the expected benefit (that is, by the cost–benefit ratio) until the budget is fully allocated. This first factor makes it possible to combine the projects' positive aspects (fulfilling the objective) with their negative aspects (the consumption of resources, in this case, the available budget);
- On the other hand, the fact that projects are indivisible may mean that to achieve the highest and best use of available funds, projects (or groups of projects) may be chosen that do not have the highest cost–benefit ratios but that make a greater total contribution to the objective function by using financial resources that would otherwise go unused due to the indivisibility of the projects.

It is only by solving the optimisation problem as it has been proposed that the use of the available budget can be efficiently organised with regard to the indivisibility issue, assuring that the objective of recovering the abandoned mining areas will be achieved to the greatest extent possible, considering the technical and budgetary constraints.

If the choice were made to prioritise projects in descending order of their absolute value to the objective (Scenario A), respecting the budgetary constraints in place until the end of 2006, and if the following technical restrictions were imposed, then:

- The Aljustrel sub-projects can only be undertaken after the previous stages have been completed, but this could be done in the same period;
- The additional work in the Serra da Caveira can only be undertaken if the dam recovery project is undertaken;
- The second and third projects of the São Domingos mine could only be undertaken if the first project is also undertaken, but each of these projects is independent of the other;
- The Cunha Baixa, Espinho, and Quinto do Bispo projects would be undertaken jointly (or not at all), and the first 17 projects would be selected (see Table 3), with the exception of the additional works in the Serra da Caveira because the dam recovery project was not chosen. If there are still funds available after these 16 projects, as many of the following projects as the budget permits would be selected, making it possible to undertake all projects up to and including Mata da Rainha, with the exception of Santo Antonio, São Domingos (sub-project 3), and the six projects between Terramonte and Jales.

The 25 projects selected would amount to a total value of 0.5996 in the objective function, with a total investment cost of €38,687,900. It should be noted that the sum of all projects' contributions to the objective as determined by the application of the AHP model equals 1. Thus, completing the projects indicated by the objective function would represent attaining 60% of the total benefit that would theoretically be attained if all 60 projects were completed. The value achieved by the objective function can thus be interpreted as the degree to which the entire objective (all 60 mines) has been attained.

Alternatively, the selection of projects could be based on the highest cost–benefit ratio, that is, based on the result expected per euro spent (Scenario B). It should be noted that when projects are selected based on their absolute contribution to the objective, there is a tendency to favour the most expensive projects; however, when the criterion of contribution per euro is used, the trend is reversed. There is even a simple linear negative correlation coefficient of −0.35 between the rankings produced by the two criteria (Table 3).

Selection according to this criterion (Scenario B), respecting the same technical and budgetary restrictions as Scenario A, makes it possible to choose 58 of the 67 projects, owing to the removal of four projects (phases 4 and 5 of the Aljustrel project and the Urgeiriça and Vale D'Arca projects) which are among the eight most expensive projects, totalling 16 million euros, which could instead be used to undertake 37 other projects with better cost–benefit ratios. In this manner, it is possible to improve the value of the objective function by 41%, bringing it to 0.8487.

Finally, solving this problem under exactly the same constraints as those in scenarios A and B in a manner that maximises the value of the objective function (Scenario C) shows that two of the projects selected according to the cost–benefit criteria (Scenario B) would be excluded: Santo Antonio and São Domingos P2, which represent a combined absolute contribution to the objective of only 0.271 but cost €3,575,500. Instead, these would be replaced by the Rosmaneira and Vale D'Arca projects, which have a less favourable cost–benefit ratio but make a greater absolute contribution to the objective function (0.0318). The higher cost of these projects (€5,144,000) would be covered by the savings resulting from the two eliminated projects and by funds left over in the budget under Scenario B due to the indivisibility of projects.

The increase in the value of the objective function demonstrates the need to optimise available resources for the implementation of these projects (Fig. 3). This occurs for more complex situations in which there are different budgetary constraints for different time periods or types of mines. In such cases, this difference tends to be greater because the selection according to the criteria used in Scenario B is not able to well handle the combination of the intensity factor (given by the cost–benefit ratio) and the quantity factor associated with the indivisibility of the projects.

The next section includes the conclusions and suggestions for further research.

Conclusions

Decision-making in the environmental field is complex, given that there are often significant trade-offs among economic, social, political, and environmental factors, frequently involving various stakeholders with different goals, priorities, and time perspectives, in addition to a combination of several scientific fields (Kiker, Bridges, Varghese, Seager, & Linkov, 2005). In these circumstances, MCDA is often helpful in making decisions about resources (Pollard et al., 2004) and has even been recommended for the European Union (Thornton, Franz, Edwards, Pahlen, & Nathanail, 2007).

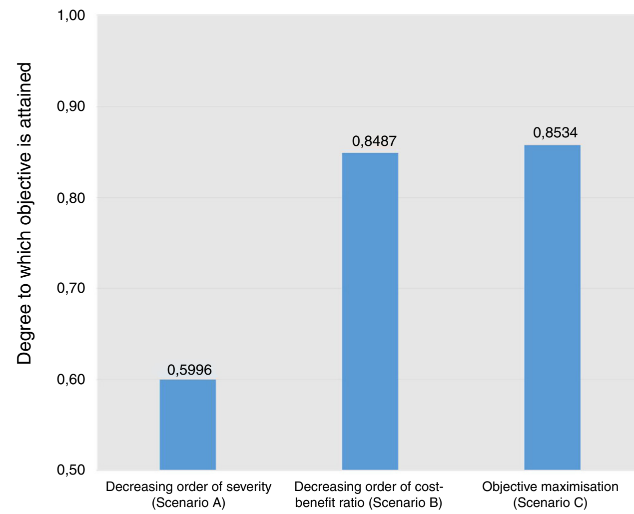

Fig. 3. Benefits of optimisation.
Source: Research data.

Moreover, the need to combine qualitative analytical criteria with a quantitative approach can be met by the AHP (Forman & Gass, 2001; Vargas, 1990), which is also useful in at least partially limiting possible analytical bias in the implementation of specific objectives, particularly when several experts meet to discuss and make decisions (White & Bourne, 2007).

In the case examined here, in addition to these factors (diverse objectives, qualitative and quantitative criteria, various stakeholders), budgetary restrictions made optimisation necessary, using integer programming to ensure the efficient allocation of scarce resources, a key element in the development of every economic theory.

This article represents a contribution to this line of research – interventions in the recovery of abandoned mining areas/brownfields – presenting a real case in which the AHP methodology is applicable to the selection of mines for intervention, bearing in mind the objectives and criteria defined and decided upon by a panel of experts. This provided a well-grounded method to better achieve the goals, transcending more limited views that call for the prioritisation of mines requiring the largest investment due to the higher severity of the situation.

However, this entire analysis is based on comparisons among homogenous groups of mines in light of various criteria, which is limited (according to the classical AHP approach) to a predefined scale ranging from −9 to +9; the influence of this limitation on the final results should be analysed in future studies. The fact that the greatest possible difference between pairs being compared is limited to a scale of nine may be insufficient to correctly represent the degree of difference between groups in cases in which the groups are very diverse. Along the same lines, further studies may test other methods of multi-criteria analysis, overcoming other limitations of the AHP identified by Smith and Von Winterfeldt (2004) and by Bana e Costa and Vansnick (2008).

Conflicts of interest

The authors declare no conflicts of interest.

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