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Selection of optimal land uses for the reclamation of surface mines by using evolutionary algorithms

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ABSTRACT

A methodology for the selection of the optimal land uses of the reclamation of mined areas is proposed. It takes into consideration several multi-nature criteria and constraints, including spatial constrains related to the permissible land uses in certain parts of the mined area. The methodology combines desirability functions and evolution searching algorithms for selection of the optimal reclamation scheme. Its application for the reclamation planning of the Amynteon lignite surface mine in Greece indicated that it handles effectively spatial and non-spatial constraints and incorporates easily the decision-makers preferences regarding the reclamation strategy in the optimization procedure.

1. Introduction

Land reclamation and the related post-mining activities play a vital role in every mining project. The selection of the most appropriate land uses of the reclaimed mined area is a key point in the overall process. However the selection of the most appropriate land uses is a complicated multi-criteria decision problem because of the variety of the criteria and parameters (geotechnical, environmental, legal, economic, social) which are taken into consideration and the necessity to attain the acceptance of the reclamation plan by local communities [1–5]. The complexity of the problem is further increased due to nature of social and environmental constraints and to subjectivity that characterize the decision makers, like local authorities or local communities [1,3,6].

Many studies have been published for land reclamation and land use selection in mining industry. The majority of them focus in ranking or prioritizing a number of potential land uses (alternatives) leading to the selection of a single land use for the whole mined area. Such a selection is achieved by applying multi-criteria decision-making (MCDM) approaches [1,3,7–9]. An example of the MCDM approach is the development of the analytical hierarchy process (AHP) methodology that assesses the priorities based on the inputs of specialists in mining industry activities. AHP handles the qualitative and quantitative criteria that are related with reclamation problems and allow the decision team to examine systematically, compare and determine the priorities of the relevant criteria and sub-criteria. Based on this information, the reclamation alternatives can be compared effectively and the optimum one can be selected [3,10,11].

Mined land suitability analysis (MLSA) combines analytical hierarchy process methodology (AHP) and the ELECTRE multi-criteria decision analysis methods. The abbreviation ELECTRE denotes ELimination Et Choix Traduisant la REalité (Elimination and Choice Expressing Reality). This combination is used for the evaluation of the mined land suitability for the various alternatives. The AHP estimates the global calculated weights of the attributes evaluated by decision maker's subjective judgments and then, the weights passed to the ELECTRE method so that the most efficient post mining land uses could be appointed through comparisons of pair-wise dominance relationships between alternatives [12].

Fuzzy comprehensive method, and more specifically the multi-level comprehensive evaluation method combined with GIS, is another MCDM technique that has been suggested for selecting the most appropriate land use among various alternatives. The main advantage of this method is that it can be adjusted in an easy manner and it can objectively determine pros and cons of complicated models with multi-attributes, multi-factors in which quantitative and qualitative methods co-exist. It can also classifies different reclamation programs based on the comprehensive evaluation values which are suitable for the problems with large amounts of information, more evaluation indicators and more complicated reclamation programs [7].

However, few methods, in terms of optimization of land reclamation, have been issued taking into consideration the spatial

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variation of the decision-making parameters in a mining area [1,13]. According to the reclamation of each different parts of the post-mining area is to be provided, thus a spatial decision support system must be developed and implemented [1]. The proposed spatial decision support system (SDSS) involves two main steps: at the first stage the elaboration of the qualitative information is taking place. This information includes the negotiation conclusions among stakeholders, the existing legal framework regarding land reclamation and uses, as well as, the economic prospects. Based on this information a set of possible land uses are initially determined. In the next step the spatial analysis is performed. The mined area under reclamation is divided into several smaller parts (squares) and the decision criteria with spatial character are considered in order to select the most appropriate land use for each square. All the alternatives suggested are resulted from the previous stage. A number of technical and social criteria are considered for the characterization of land suitability for each of the possible alternatives. Hence, the second step is the heart of the decision model. Binary linear programming procedure (branch and bound algorithm) is applied for the determination of specific land uses. The applied constrains referred to the maximum and minimum area allowed for each specific land use.

However, it is well known that numerous additional constraints, mainly of spatial nature, are considered during the selection of the land uses. These constraints usually refer to compatibility of specific land uses of adjacent areas, to exclusion or inclusion of specified mined areas for a particular land use and to the number and shape of created sub-areas for each land use. The existing methods are not capable in handling efficiently such constraints considered during reclamation planning, thus the derived land use maps must be corrected manually by the reclamation planning team. This is a time-consuming procedure and do not always lead to optimal solutions, thus the need for developing a more sophisticated SDSS for the selection of the optimal land uses is necessary.

In this work an advanced SDSS as a tool for selecting the most suitable land uses is developed. Constraints regarding the proximity between the potential land-use alternatives, as well as, constrains regarding the area of each alternative land use are considered. Because of the complexity in structure and the spatial nature of these constraints, the optimization problem cannot be handled effectively by classic linear programming algorithms. Thus, the proposed advanced methodology incorporates evolutionary algorithms and desirability functions to overcome such optimization complexities.

The structure of this study is as follows: first the problem for the selection of the optimal land uses of reclaimed mined areas is described, next the methodology for the selection of the optimal land uses is presented and finally the proposed methodology is applied for the planning of the reclamation of the Amynteon surface lignite mine in Greece.

2. Reclamation of mined areas-criteria for selection of the appropriate land uses and related constraints

The main outcome of the planning of land reclamation in an area that is affected by surface mining is a thematic map which indicates the specific land uses for every part of the area.

The decision for the most suitable land use for each part of the mined area is based on the findings obtained from the area's characteristics, the opinions of experts, the development plans of local communities and authorities, the legal environmental framework and the environmental restrictions. The resulting map illustrates the reclaimed area divided into coloured squares, where each colour corresponds to a specific land use. The most common land uses of the reclaimed mined areas include agricultural land, forest, residential area, recreational area and industrial zone. The deepest part of the mined area is usually reclaimed to form a lake.

For the selection of the most appropriate land use for each square of the reclaimed area, a number of criteria, mainly of spatial nature, are considered. Experts in field of land reclamation select the decision parameters and their optimum values for each land use. A typical set of such criteria with the considered as optimum values is shown in Table 1. The values of these parameters represent the suitability of a square of the area for a specific land use according to the corresponding criterion. The land use suitability is usually expressed by applying a three-level scale: 0 for low, 1 for medium and 2 for high suitability. The most desirable (optimal) land uses for the area are those with the minimum deviation from the optimum values while at the same time satisfies numerous general (with non-spatial character) and spatial constraints.

The non-spatial constraints refer to the expressed preferences regarding the total area covered by a specific land use. Such a preference can be expressed as: 'the agricultural land must be at least 1×10^7 m^2, or 'the industrial area must be less than 4×10^6 m^2, or in a more complicated form such as: 'the desirable forestry land is 4×10^7 m^2, however it should be at least 3.5×10^7 m^2 (1 ha = 10,000 m^2).

The spatial constraints are classified into those related to the compatibility of specific land uses of adjacent land squares (proximity constraints) and into those related to obligatory exclusion or inclusion of pre-determined mined areas for a particular land use. Such constraints can be expressed as: 'recreational area must not be adjacent to industrial area' or 'the bottom of the mined area must form a lake', or 'a zone of forest must be created around the lake'.

The simultaneous fulfillment of general and spatial constraints during the selection of the optimal land uses for each square is not always attainable. To overcome this problem in the developed methodology, the general constraints referring to the area of each land use were transformed to additional optimization functions, where the preferable area of each land use was considered as the target value. Hence, the single optimization problem is transformed to multi-objective optimization problem and the only remaining constraints were those with spatial nature.

Spatial constraints were considered more important than general constraints since the first is almost exclusively related to legal end environmental regulations and their fulfillment is essential. Therefore an algorithm to examine the accomplishment of spatial constraints in the generated land use maps during the reclamation planning process was developed. If spatial constraints are not met in a square of the map then the land use of the square changes according to certain rules embedded in the algorithm. A typical example of such a case is shown in Fig. 1, where the restriction regarding the proximity of recreational and industrial zone areas is violated.

3. Methodology for selection of optimal land uses

3.1. Model development and mathematical notations

The development of the model for the selection of the most suitable land uses in the reclamation planning includes the following steps:

(1) The L different permissible land uses and the K evaluation criteria (decision parameters) are defined.
(2) The optimum value for each decision parameter corresponding to a specific land use is determined (Table 1). These optimum values form matrix $B \in R^{K \times L}$.