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Abstract: The rehabilitation of contaminated sites is a complex process encompassing technological, environmental, socio-economic aspects. These aspects show close spatial and temporal inter-relations. Moreover, mega-sites (hundreds of hectares wide) require properly designed Decision Support Systems (DSS). In this work, a DEcision Support sYstem for the REqualification of contaminated sites (DESYRE) is proposed for the identification of the most effective rehabilitation interventions. The DSS is based on a Geographic Information System (GIS) framework and integrates environmental and technological databases, risk assessment models, and multi criteria procedures. It is composed of five modules: (1) characterisation, (2) risk, (3) socio-economical and (4) technological analysis, and (5) decision. The characterisation module provides all the available information on the site (e.g. chemical and hydrogeological data). It can be explored by means of GIS tools and its database is available as input to statistical and geo-statistical software, as well as to hydrogeological and contaminant fate and transport models. Moreover, it provides the definition of efficient sampling strategies, definition of contaminant distribution, prediction of transport processes and input parameters for the risk assessment module. The risk assessment module includes exposure and risk assessment models and provides outputs such as risk maps. The socio-economical assessment module addresses socio-economical constraints and benefits. The technological assessment module allows feasibility, advantages, limits and costs of different techniques to be assessed. Information from the three assessment modules, mainly in the form of indicators, are integrated in the final decisional module by means of the multi-criteria analysis (MCDA), which can play a key-role to simplify effectively this process. In the proposed DESYRE framework, the MCDA tools appear twice. When a pool of suitable technologies is to be defined, a MCDA module assigns a score to each technologies on the basis of key-criteria. In a second level, each remediation scenario proposed by the Expert is evaluated by the Decision Makers in a Group Decision Making context. The project is in progress: framework and methodology aspects were already defined, and a preliminary application was undertaken for the megasite, industrial district of Porto Marghera (ca. 3,000 ha), located on the border of the Venice lagoon. The selection of the specific MCDA options is under way.

Keywords: Contaminated sites; Risk Assessment; Multi-criteria decision analysis; Remediation technology.

1. INTRODUCTION

Several billions Euro in the EU and several billions of dollars in the USA are spent each year for remediation of land affected by contamination. Decision-making, in the face of uncertainty and multiple and often conflicting objectives, plays a vital and challenging role in the environmental and economic management. The task of effective resources allocations has thus become especially difficult being dominated by huge uncertainty and consequent risks.

In addition, it is unlikely that any single person will have the knowledge to perform all the analysis required in supporting the overall decisions pertaining to the management of land contamination. It is also apparent that there are many specialist underpinning decisions (e.g. what risk levels are acceptable, what to sample, when to sample, what technologies should be used, etc.) that need to be made before general decisions on the reuse of contaminated land can be made.

In order to facilitate this complex decision process several attempts have been made to codify specialist expertises into decision support tools

[Bardos et al., 2001]. The uses envisaged for a decision support system (DSS) include identifying realistic management choices and integrating information into a coherent framework suitable for analysis and decision-making, discerning key information that impacts decision-making from basic information. Moreover, DSS is expected to guarantee for transparency (i.e. all parameters, assumption, and data used to reach the decision should be clearly documented) and to ensure that the decisions-making process itself is documented.

The integration of risk analysis models (for human health and ecosystem) with socio-economic evaluations and with criteria for technology comparison is fundamental to obtain the whole useful information for developing a correct decisional process. All information should be elaborated in order to define different alternatives of effective rehabilitation interventions and efficient remediation actions, which represent the different decisional scenarios. These alternatives should be described by some index (e.g., risk index, socio-economic index, etc.) and should be evaluated by mean of some specific criteria, which constitute the decision rules. The latter are ultimately the result of the application of multi-criteria analysis.

In recent years, considerable interest has been focused on the use of Geographic Information Systems (GIS) as a decision support system [Eastman et al., 1993]. In fact, they are able to develop several spatial elaborations of basic information (e.g., spatial distribution of contaminants into different environmental media, dislocation of the different remediation technologies, etc.) and of above-mentioned indexes. Moreover, the integration of Decision Science's tools into GIS software appears highly stimulating. However, exploration into this area [Eastman et al., 1993] indicated that the tools available for this type of analysis were remarkably poor.

In order to fulfil a present lack of integration between GIS and decision analysis tools, the project DESYRE, founded by Italian Ministry for University and Scientific Research was undertaken. It started in March 2001 and will end in March 2003. Here we report methodological results acquired so far.

2. DESYRE FRAMEWORK

We can divide problems related with contaminated macro-sites rehabilitation in three main fields: site characterization and data processing, evaluation of the risk, choice of proper remediation technologies. The structure of DESYRE was built trying to solve these problems to support the Expert to gain a comprehensive view of the rehabilitation process and to choose the best solution. The main results of this effort is the link of tools such as GIS, risk analysis, socio-economic analysis and technologies comparison to reach the target. GIS is used to elaborate spatial datas, risk analysis (RA) is used to zone the site according to risk levels associated to contaminants type and concentration, technologies comparison module (TC module) develops rationale choose of the "best remediation technologies".

The TC module is developed according to a stepwise structure. The first step selects suitable technologies, taken international review on the basis of site and contaminants criteria. This operation creates a pool of remediation technologies that is included as input in the flow chart of the DSS (Figure 1). Technologies in the pool are described by key-criteria and a system of scores, while an additional table provides infos about technologies unsuitable to be applied together. The next step is to find out where it is necessary to remediate and how, so we introduce the RA in order to have a zoning of the site according to risk level.

The main goal of the risk analysis module, applied to the decision support system, is to integrate the environmental evaluations into the decisional process for the rehabilitation of contaminated sites. The risk estimate is, however, only one factor used in contaminated land decision making, together with socio-economic and remediation technology factors.

The risk analysis applied to contaminated sites is a technical procedure [US-EPA, 1989; ASTM, 1998] carried out to define risks posed by the site contamination to the human health and the land remediation interventions on the basis of the site characterisation, the quantification of human receptors exposure to the contaminants, and the contaminants toxicity assessment.

The site characterization is the first step of the risk analysis and requires the qualitative and quantitative representation of the contaminant source and as much of the data necessary for modeling contaminant fate and transport. It involves the identification of the chemicals present at the site, their concentration and spatial distribution. The spatial distribution of contaminants is required for identify the size and representative concentrations of contaminant sources and it is performed by using geostatistical methods. The main geostatistical tools are the variography and the Kriging [Isaaks and Srivastava, 1989]. The variography is used to quantify and to model the spatial correlation between sample location. The Kriging is used to get interpolation from observed values and their spatial relationships, as inferred from the variography. The application of these tools lead to determine areas of the site with homogeneous contamination. The receptors exposure represents the core of risk assessment and it is defined as the contact of humans with chemicals. Exposure assessment leads to the quantification of the magnitude, frequency, duration and routes of exposure. The toxicity assessment determines the exposure dose-health effect relationship for each contaminant.

The risk analysis performed for the decision support system leads to investigate two types of contamination sources, respectively, the soil and the groundwater. It has to be noticed that all chemicals were gathered into six classes (nonhalogenated volatile organic compounds, halogenated volatile organic compounds, nonhalogenated semivolatile organic compounds, halogenated semivolatile organic compounds, fuels and inorganics) since the compounds of each class can be treated by the same remediation technologies. The possible exposure pathways are the ingestion and dermal contact with soil, the inhalation of vapour and particulate emissions, and the groundwater ingestion.

The risk analysis is applied twice times inside the decision support system: the first time for pre-remediation evaluation. In this phase the risk analysis is performed for each homogeneous area and for each contaminant class. As far the soil contamination, the risk analysis defines maps of risk based on actual contamination. There is one map for each contaminants class (six maps in total). All maps point out the areas with a non acceptable risk for human health which need a mitigation intervention. The same procedure is applied for the groundwater contamination.

After the risk analysis development, the Expert assigns all remediation technologies suitable for each risk homogeneous area. Finally, the system verifies the assignment of the remediation technologies on the basis of their performance. It can warn about the need of a “train technology”.

Thus, on the basis of RA the Expert can assign to each zone the proper remediation technology. The Expert assigns weights to key-criteria in order to have a ranking of the technologies chosen. The software elaborates the ranking and some spatial infos like distribution maps for type of technology, covering area, etc., to have a defined view of all the feasible remediation options. The Expert evaluates scores and datas and prepares the technologies sets suitable to meet the remediation objectives. The sets are a combination of technologies extended spatially and temporally, composed by train technology. These sets are evaluable through the scores that their technologies have. Effectiveness of the remediation technologies is evaluated on a test scale and the performance is introduced in the second risk analysis to evaluate the efficiency of each set in achieving the remediation target. This post-remediation risk analysis produces the risk based maps that outline the residual risk after the application of the mitigation interventions. The areas with a non acceptable residual risk are highlighted on the maps, to allow the Expert to define safety measures. At the end, the risk analysis module identifies a risk based index in order to compare the different remediation scenarios on a risk reduction base.

The Expert composes each "remediation scenario" on the basis of the risk analysis results, the data on technologies sets and all the infos processed and collected. A scenario is an inclusive and suitable solution for the rehabilitation of a contaminated site, it includes the description of the technologies pool needed to remediate the contaminated matrix, the feedback on health, environmental and socio-economic conditions, the solution is explained with a comprehensive spatial and temporal view. In the decision module each scenario is described by the key-criteria for technologies, for the RA, and for the socio-economic analysis (not reported here). The rehabilitation solution is described by a system of criteria and scores and expressed in a matrix form. This clear final step allows stakeholder to choose the preferred option and to apply a sensitivity analysis.

Finally, the strengths and peculiarities of DESYRE are: (a) it requires an active role of the Expert in order to avoid any simplifications triggered by a non user oriented application of the DSS; (b) the connection among tools working in modules of a step on structure in order to investigate every aspect of the problem; (c) the policy to found the choice moments on a transparent system of criteria estimated by scores and indexes processed by Multi Criteria Analysis.

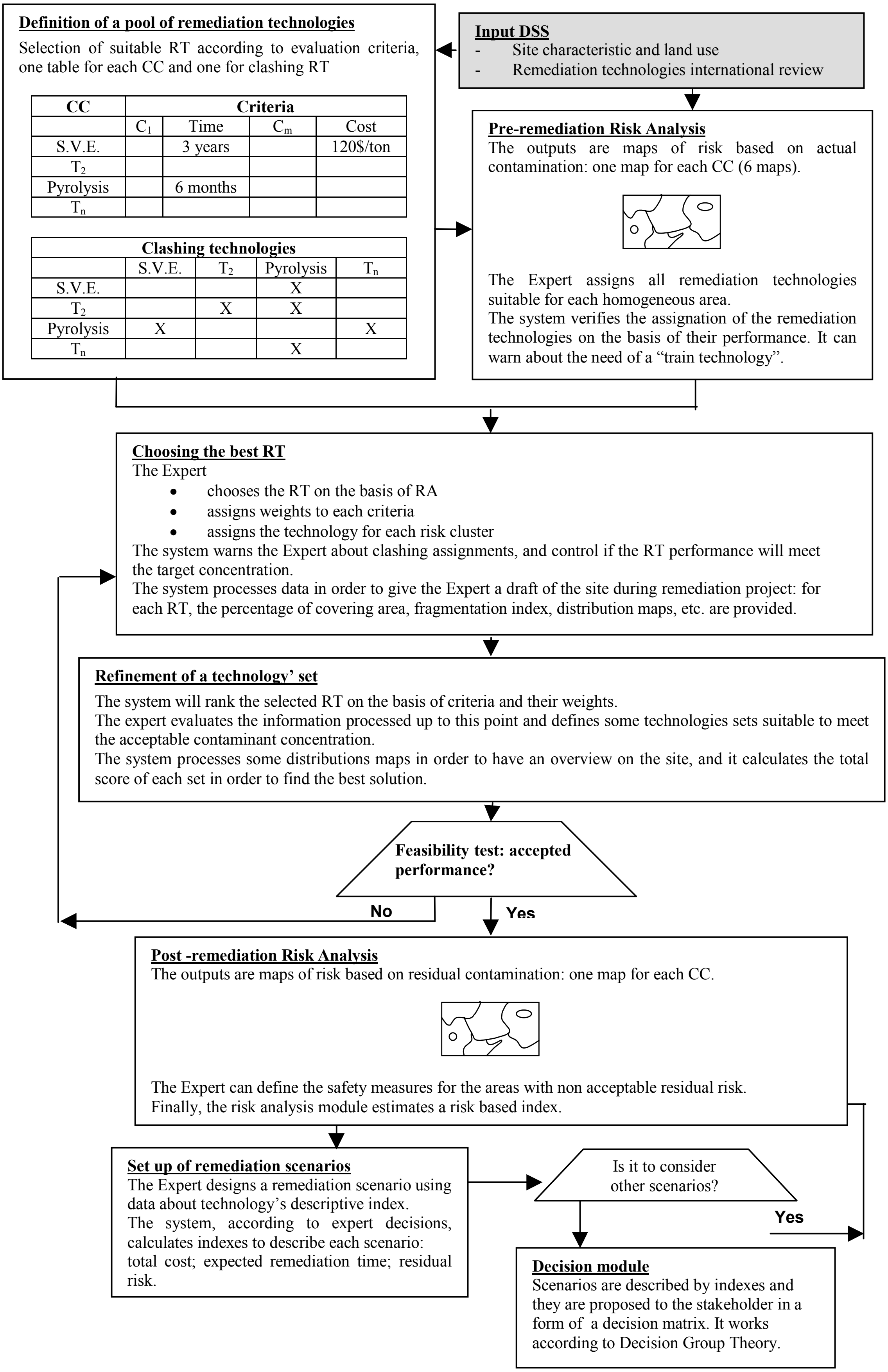

Figure 1. The DESYRE framework (RT: remediation technology; CC: contaminant class; RA: risk analysis).

3. MULTI-CRITERIA ANALYSIS

In the proposed DSS, the Multi Criteria Decision Analysis (MCDA) plays a key-role to help both the Experts and the Decision Makers. In some sense, the MCDA tool is the core of the DSS, its importance about the overall decision process being universally accepted. This is particularly true for environmental decision problems, characterised by an high level of complexity [Munda, 1994]. The MCDA approach consists of a structured procedure to help a potential decision maker, in presence of possibly conflicting targets. In MCDA problems, the decision scenario is represented by a two-entries table, where each row corresponds to an alternative, and each column to a criterion. Naturally, each alternatives has to be described by the same number and type of criteria. Each alternative can then be represented by the *vector* of its criteria values. Only in few cases we are able to discharge the *dominated* alternatives, the ones whose criteria values are equal or worst than an other alternative (the term *worst* has to be intended in a relative sense, depending if a criterion is a benefit or a cost). In the most cases, after the elimination of the dominated alternatives (if any exists), the decision maker needs to solve the problem of *selecting* the best alternatives (optimal choice problem), or of *ranking* all the remaining ones (ranking problem). For instance, let us consider the case of two benefits only. What to do if the value of the the first benefit in the *i*-th alternative is higher than the value of the *j*-th alternative, but the contrary is true for the second benefit? Clearly, the ranking depends on how much greater is the importance that the decision maker assign to one benefit with respect to the other one. Various approach exists in the literature on MCDA problems to solve those conflicts. Some Author classify them as *multiple attribute utility theory* methods, *outranking* methods, *interactive* methods, while other ones uses different classification (by information, by data type, and so on), see Chen [1992], Vincke [1992]. Another distinction regards *compensatory* and *non-compensatory* methods, in the former case interaction among attributes is possible. A lot of MCDA methods are available at the actual state of the art, but a complete scenario is beyond the purpose of this contribution. Among the most appealing ones, we limit to quote the PROMETHEE, the TOPSIS, the AHP, the ELECTRE, the rough set approach, the aggregation operators (like the family of OWA introduced by Yager [1988]), and the fuzzy ranking methods. Among the last ones, of particular interest is the method proposed by Carlsson et al. [2000], as a fuzzy extension of the conjunctive method, together with the use of OWA operators. One of the most diffuse approach is the simple additive weight method (SAW), in which all the criteria values are weighted by a suitable real number measuring the importance of the weights and subsequently added. Although its simplicity, the SAW method is characterised by a serious drawback: no interaction among the attributes is admitted, since the *preferential independence* axiom is required. Moreover, some difficult exist for the weights assignment. To this purpose, some methods like AHP can be suggested, see Saaty [1980], and also other tools such as fuzzy logic, the Choquet integral, and the theory of aggregation operators, see Chen et al. [1992]. Another characterisation regards the question if the problem need to be approached by a single decision maker, or by a group of Experts or decision makers. In the latter case, we speak about *Group Decision Theory*, for which the *consensus measures* are an important item, showing how much the group of decision makers agree or disagree about the alternative ranking, see for instance Carlsson et al. [1992].

In the proposed DESYRE framework, the MCDA tools appear twice. At the beginning, when a pool of suitable technologies is to be defined, a MCDA module assigns a score to each technologies, on the basis of key-criteria, like *cost*, *development time, efficiency (or performance), reliability, flexibility, public acceptability* and so on. This method is applied to each set of technologies chosen by the Expert. In a second level, each remediation scenario proposed by the Expert is evaluated by the Decision Makers in a Group Decision Making context (see later). Due to the fact that both numerical and logical data appear in the criteria definition, we suggest to implement a modified version of the classical TOPSIS method, the so-called BB-TOPSIS [Rebai]. We propose this approach because its simplicity and intuitive meaning. In the basic TOPSIS method all the criteria values are supposed numeric, and, after a normalisation in the scale [0,1], the so called *ideal* and *anti-ideal* alternatives are computed. The ideal alternative is the one characterised in the *j*-th attribute by the highest value (among the ones present in the available data), while the anti-ideal alternative collects the lowest values. Then, for each alternative, the algorithm computes the weighted distances between both the ideal and the anti-ideal alternatives, and a *separation* index is computed as the ratio between the distance from the anti-ideal alternative and the sum of both the two distances. Finally, all the alternatives are ranked according to such index. About the reasons for which the separation index can be a good candidate for the ranking, see the quoted references. The BB-TOPSIS approach is based on the concept of *fuzzy bag*, a collection of couples objects-weights. A bag is assigned to each alternative, where each (first) element, for each criterion, is the count of alternatives that are dominated. In so doing, both numerical, logical and linguistic attributes can be treated. The rest of the algorithm is similar to the basic TOPSIS version, with some suitable modifications, see [Rebai]. A problem regards the choice of weighting factors. Some past experience advises the use of a modified version of the AHP approach, the *multiplicative* AHP in a Group Decision Making context (GDM), see Ramanathan et al. [1994], Van Den Honert at al. [1996]. This approach is particularly attractive because the hierarchical properties of the AHP methodology. Note that the GDM can be of great usefulness in this phase, if two or more Experts discuss their opinion each other, even in presence of reciprocal conflicts. Furthermore, some consensus measures can be easily introduced in this framework, and the degree of importance of each Expert can be automatically defined by the procedure itself using a devoted session. In this phase, all the Experts assign a pair-wise comparison of all the couples of criteria, and subsequently the AHP methodology provides the computation of the importance weights. Moreover, an interactive phase helps the Expert to insert or delete some alternatives during the process.

The MCDA analysis will be implemented also at the evaluating step of rehabilitation scenarios (decision module in Figure 1), when all the scenario is shown to the (public) Decision Makers (DM), such as stakeholders. The DM have to decide on the basis of even different items than the Experts, also politician and economic impact factors need to be considered. This phase is actually still under development, but, from methodological point of view, no substantial differences exist from the previous one. Finally, we remark that a separated analysis will supply a socio-economic analysis using a fuzzy expert system that, in a wider sense, can be regarded such as an innovative MCDA approach.

4. ACKNOWLEDGEMENTS

DESYRE was founded by the Italian Ministry for University and Scientific Research.

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