

The role of Multi-Criteria Decision Analysis in a DEcision Support sYstem for REhabilitation of contaminated sites (the DESYRE software)

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Abstract: The rehabilitation of contaminated sites involves several considerations in terms of environmental, technological and socio-economic aspects. A decision support system becomes therefore necessary in order to manage problem complexity and to define effective rehabilitation interventions. DESYRE (Decision Support sYstem for Rehabilitation of contaminated sites) is a software system which integrates risk assessment with socio-economic analysis and technological assessment in order to provide decision-makers with different remediation scenarios to be evaluated. The structure of the system allows a subsequent analysis, from socio-economic analysis and site characterization, to risk assessment before and after remediation technologies selection, until the definition of remediation scenarios. The system integrates several analytical tools, such as geostatistics, Fuzzy logic, risk assessment and geographical information systems (GIS). The present paper focuses on the role of the Multi-Criteria Decision Analysis (MCDA), which represents the core of the DSS. In the DESYRE framework, MCDA is applied for the definition of the pool of the suitable remediation technologies. The analytic hierarchy process is applied to rank technologies and develop alternative remediation scenarios. The scenarios are described by a set of indices which can be aggregated by decision makers to rank alternative options. Future research developments suggest the MCDA application also for the evaluation of the remediation scenarios by different stakeholders, in a Group Decision Making (GDM) context.

Keywords: Contaminated sites, Multi-criteria Decision Analysis, Risk Assessment, Remediation technologies, Decision Support Systems, GIS.

1. INTRODUCTION

Decision-making on environmental issues is often a process characterized by complexity, uncertainty, multiple and sometimes conflicting management objectives, as well as integration of numerous and different data types.

In the case of contaminated sites, additional problematic aspects arise: heterogeneity of site contamination, high costs for remediation activities, presence of multiple stakeholders,

crucial integration of risk assessment with socio-economic and technological valuations. Contaminated sites management requires to perform specialistic judgements and to translate them in alternatives of rehabilitation interventions. Therefore, a decision support system is needed in order to provide coherent and realistic management scenarios, by linking all the interested issues in a transparent and reproducible way.

Several attempts in this direction have been made in recent years (Bardos *et al.*, 2001). At the same time, Geographical Information Systems (GIS) have been recognised as valid and effective instruments in supporting decision-making, due to the possibility of spatial elaborations of different information (Eastman *et al.*, 1993).

The DESYRE (Decision Support System for rehabilitation of contaminated sites) software is a successful example of these efforts of integrating risk analysis procedures with socio-economic evaluations and technology assessment in a supporting GIS-based tool for decision-making. In a first phase, DESYRE provides assessment modules for a multi-disciplinary team of experts, composed of risk assessors, socio-economists and technology engineers. The experts are supported along all the analytical steps, from site characterization to socio-economic valuation and technologies ranking, until the definition of different remediation scenarios to be presented to the final decision-makers. In the last phase, DESYRE provides decision makers with tools for comparing alternative remediation scenarios.

During one of the analytical phases, DESYRE implements a Multi-Criteria Decision Analysis (MCDA). The importance of the application of a MCDA procedure in a decision process has been widely recognised. In fact, given the high level of complexity of environmental decision problems, MCDA represents a fundamental help for the decision maker in the presence of possibly conflicting targets (Munda, 1994). Moreover, this methodology assures great transparency to the whole decisional process.

The paper will first present the general organization of the DESYRE software. The second part will be focused on the Multi-Criteria Decision Analysis, encompassing what has been already implemented and future developments.

2. DESYRE GENERAL PRESENTATION

DESYRE software is the result of a three-year project funded by the Italian Ministry for University and Scientific Research. DESYRE main objective is the creation and comparison of different remediation scenarios in terms of residual risk, technological choices and socio-economic benefits.

Addressing the cited main objective, DESYRE software allows the user to perform subsequent analysis of site characterisation, risk assessment, technologies selection and scenarios construction. By applying different and specific tools provided in the system, such as Fuzzy logic and Multi-criteria Decision Analysis, geostatistics methods

and GIS tools, the system allows to investigate each aspect of the contaminated site remediation process in a stepwise procedure. Application is facilitated by the user-friendly interface and the clear guideline, where all parameters, assumptions and data, in addition to final results, are clearly visualized and highlighted. For instance, it is possible to create chemical databases and GIS-based risk maps. Moreover, transparency for the decision process is guaranteed by the use of Multi-criteria Decision Analysis methodologies and effective analysis is assured by the active role of experts within the whole process.

As stated above, DESYRE organisation through a stepwise procedure assists the analytical and decisional process development (Figure 1).

First stage is the socio-economic analysis. Since remediation objectives are strictly related to socio-economic drivers and constraints, the provided analysis, based on a Fuzzy expert system, allows to select the most attractive land use to be considered in the risk assessment (Facchinetti *et al.*, 2003).

Subsequently, a site characterization is performed, which provides the analysis of spatial distribution of contaminants by using geostatistical methods (in particular, variography and Kriging), in order to define areas of homogenous contamination. Analysis is carried out both on soil and groundwater.

Risk assessment (US-EPA, 1989; ASTM, 1998) is then performed twice during the process, before and after the simulation of treatment performances of selected technologies. The first assessment provides a site zoning according to risk levels; the second one allows to evaluate the residual risk after the application of a technological set. In both cases, exposure pathways (such as ingestion, dermal contact or inhalation) as well as interested receptors like humans or waters are considered. Six classes of chemicals are identified, related to technological treatment capabilities:

- non halogenated volatile organic compounds,
- halogenated volatile organic compounds,
- non halogenated semivolatile organic compounds,
- halogenated semi-volatile organic compounds,
- fuels
- inorganics.

Between the first and the second risk assessment phase, the selection of technologies is proposed to the user. A first collection of suitable technologies is made considering the general characteristics of the whole site and contaminants of concern. Then, a more focused selection is performed by assigning specific technologies to identified risk areas. Technologies are ranked on the basis of key-criteria such as cost, time, efficiency, reliability, public acceptability. For the technologies ranking,

a Multi-criteria Decision Analysis is performed. Experts are called in this phase to provide knowledge and expertise by assigning technologies to each homogenous risk area, with the option of creating several sets of technologies applied differently in space and time. The system allows then to run the risk assessment procedure again in order to evaluate risk reduction and residual risk levels.

Finally, on the basis of results from previous investigations, remediation scenarios are identified. In this decisional phase, alternative scenarios can be compared on the basis of a set of indices derived from the technological selection, the risk assessment procedure and the socio-economic analysis. A comparative matrix is therefore presented to the stakeholders involved in the decision-making process.

DESYRE software has been tested in two areas (450 and 43 hectares wide, respectively) of the mega-site of Porto Marghera, Italy. Porto Marghera is a 3,600 hectares industrial (mainly petro-chemical) zone, located at the border of the Venice lagoon. Common contaminants are PAHs, amines, dioxins, halogenated organic compounds and metals (such as As, Cd, Pb, Zn).

According to the Italian Law 426/98, Porto Marghera is the largest contaminated site of national interest in Italy. For this reason, it has represented a challenging opportunity for the application of the DESYRE software, which aims at the integration of risk assessment with socio-economic and technological valuations in large contaminated sites with conflicting social and economic drivers and pressures.

Moreover, the application has been instrumental for evaluating technological indications provided within the Master Plan developed for the same area, and for comparing them with the software elaborations.

The scenarios provided by the application of the DESYRE software have highlighted the usefulness of DESYRE in supporting decision making through the constitutions of different alternatives. Proposed solutions have been characterized by great variety in the different considered parameters, from costs to time duration, technology performance and environmental impacts. DESYRE outlined advantages and limitations of each option, as a necessary basis for the creation of a broad consensus on a final choice among multiple stakeholders.

The verification of the DESYRE DSS through the experimental application to the two case-studies is the object of a specific manuscript in preparation, to be submitted for publication.

4. MULTI-CRITERIA DECISION ANALYSIS WITHIN THE DESYRE FRAMEWORK

The Multi Criteria Decision Analysis (MCDA) is the core of the DSS. In the considered MCDA problem, the decision scenario is represented by a two-entries table, where each row corresponds to an alternative, and each column to a criterion. Each alternative can then be represented by the vector of its criteria values. After having discharged the dominated alternatives (the ones whose criteria values are equal or worst than other alternatives) the decision maker needs to solve the problem of selecting the best alternatives, or of ranking all the remaining ones. Various approaches exist in the literature on MCDA problems to solve possible conflicts among criteria. A feasible classification consists of multiple attribute utility theory, outranking, or interactive methods, but even other classification are possible, for instance, based on compensatory and non-compensatory methods (Chen *et al.*, 1992; Vincke, 1992). Anywise, a complete scenario of the available methods is beyond the purpose of this contribution. Among the most appealing ones, we limit to quote the PROMETHEE (Brans *et al.*, 1986), the TOPSIS (Chen, 2000), the AHP (Saaty, 1980), the ELECTRE (Roy, 1989), the rough set approach, the aggregation operators (like the family of OWA introduced by Yager (1988)), and the Fuzzy ranking methods. 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 difficulty exists for the weights assignment. To this purpose, some methods like AHP can be suggested (Saaty, 1980), and other tools such as Fuzzy logic, the Choquet integral (Murofushi and Sugeno, 1989), and the theory of aggregation operators, (Chen *et al.*, 1992). Another characterisation regards the question if the problem needs 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 (Carlsson *et al.*, 1992).

In the DESYRE framework, the MCDA tools are applied first in the definition of the pool of suitable technologies and second for the comparison of alternative scenarios.

With concern to the technologies selection, a score is assigned to each technology 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, and it is similar to the SMART approach (Lootsma, 1997; Lootsma, 2000; Triantaphyllou, 1999). Afterward, to each criterion a weight is assigned, with the aim of enhancing its relative importance. The weight assignment phase is performed using the AHP approach, both with the Saaty method and with the multiplicative approach. In both the approaches, the decision maker (in this case the environmental engineering expert) is asked for a comparison among each couple of criteria. In the Saaty method, those values belong to the integer scale (1, 2, 3, 4, 5, 6, 7, 8, 9) and their reciprocal, while in the multiplicative approach the geometrical scale is used. The two approaches also differ for other items, like the computation of the aggregated judgments. The interested reader can refer to the quoted references. Moreover, some algorithms are applied to compute the consistency of the judgments (inconsistency appears where the transitivity property between three judgments is violated), thus helping the decision maker to revise its judgments about the comparison between a couple of criteria. Note that the AHP approach is applied only to the weights assignment phase, and not to the scoring of the criteria values. This is mainly due to the fact that the number of possible alternatives (decontamination technologies) can be quite large, and the number of required comparisons could be unacceptable. Then, we preferred to directly evaluate the alternatives by the Expert on the basis of some lower lever sub-criterion.

The second application of the MCDA within the DESYRE software regards the definition of the remediation scenarios to support decision-makers (in this case stakeholders for the remediation of the site). A remediation scenario is characterised by:

- the rehabilitation of the contaminated land to a specific land use, which is related to socio-economic benefits,
- a set of remediation technologies, which are related to costs, time duration of interventions, performance reliabilities and environmental impacts,

- the reduction of contaminant concentrations in soils and groundwater, which is related to a reduction of human health risk.

Therefore, a set of indices can be used to describe each scenario encompassing socioeconomic, technological and human health risk. These indices are automatically calculated by the socio-economic, risk assessment and technological modules during the creation of each alternative scenario (Figure 1). In the case of the risk and the technological indices, they are derived by aggregation of micro-indices. The technological index is based on three micro-indices: (1) rank of technologies applied, (2) number of technologies (a low number is preferred), (3) performance of the overall technological set. The risk index is based on four micro-indices: (1) residual risk in terms of magnitude, (2) residual risk in terms of surface, (3) risk benefit, (4) risk uncertainties. A detailed description of indices is the object of a specific manuscript in preparation.

The aggregation of micro-indices into the technological and risk indices are performed by experts through SAW methodologies. While SAW has been adopted in this preliminary stage, the use of OWA (Ordered Weighted Average) operators, or Choquet integrals or AHP can be evaluated in future implementations.

All indices are normalised in a 0-1 scale and provided to decision makers for ranking alternative scenarios. The optimal scenario is always a compromise among socio-economic and risk benefits, technological reliability, times and costs and environmental impacts. The set of indices can be aggregated into one index according to SAW methodologies in order to rank alternative scenarios. Decision makers can adjust the weight of each index according to their preferences: e.g., local authorities can be more interested in socio-economic benefits, while land owners can be concerned with remediation costs and environment association may push for a minimum risk objective. DESYRE outpoints advantages and disadvantages of each scenario: e.g., a drawback of heavy remediation interventions is that environmental impacts may overcome the benefit of risk reduction. Indices can be displayed by means of histograms such as the ones showed in figure 2.

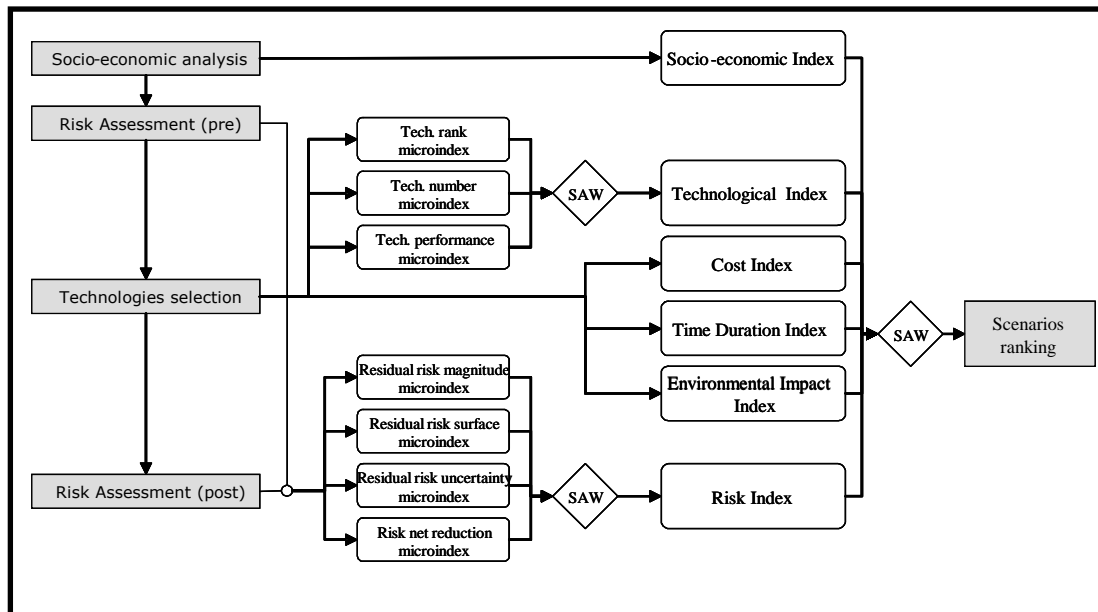


Figure 1. Derivation of indices and micro-indices in the assessment phase and their aggregation for ranking alternative scenarios.

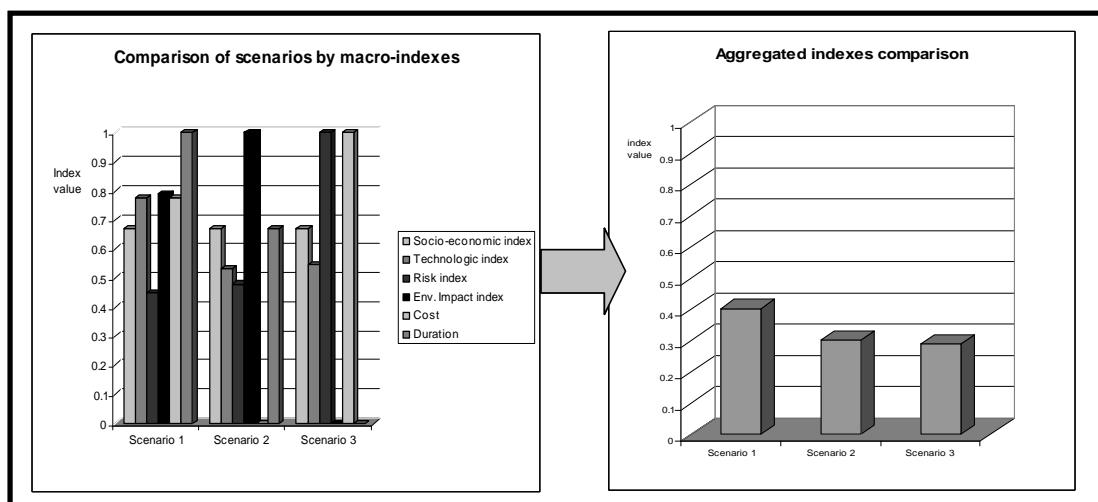


Figure 2. Example of histograms for comparing hypothetical scenarios based on socio-economic, technologic and risk indices and ranking scenarios based on the aggregated index.

5. FUTURE DEVELOPMENTS

Multi-criteria Decision Analysis has demonstrated its high potential in supporting experts in the definition of the pool of remediation technologies within the DESYRE framework.

Future research developments can be planned, in order to further implement the MCDA analysis at the decisional phase. We propose to consider the presence of multiple decision makers, thus each possible remediation scenario will be evaluated in a Group Decision Making (GDM) context, using the multiplicative AHP (Ramanathan *et al.*, 1994; Van Den Honert *et al.*, 1996). 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. Another future implementation regards the possibility for decision makers to evaluate rehabilitation scenarios on the basis of additional items beyond that provided by the experts, since

also political and economic impact factors need to be considered. At methodological level this objective does not pose substantial differences from what proposed so far. Finally, we intend to implement a modified version of the classical TOPSIS method, the so-called BB-TOPSIS (Rebai, 1993) since both numerical and logical data appear in the criteria definition, and this (simple and intuitive) method does not require a common measurement scale, nor the use of transforming functions (see the quoted references).

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