A SOFTWARE TOOL FOR SOIL CLEAN-UP TECHNOLOGY SELECTION

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ABSTRACT

Soil remediation is a difficult, time-consuming and expensive operation. A variety of mature and emerging soil remediation technologies is available and future trends in remediation will include continued competition among environmental service companies and technology developers, which will definitely result in further increase in the clean-up options. Consequently, the demand has enhanced developing decision support tools that could help the decision makers to select the most appropriate technology for the specific contaminated site, before the costly remedial actions are taken. Therefore, a software tool for soil clean-up technology selection is currently being developed with the aim of closely working with human decision makers (site owners, local community representatives, environmentalists, regulators, etc.) to assess the available technologies and preliminarily select the preferred remedial options. The analysis for the identification of the best remedial options is based on technical, financial, environmental, and social criteria. These criteria are ranked by all involved parties to determine their relative importance for a particular project.

Key words: decision support tools, multicriteria optimization, soil remediation

INTRODUCTION

Remediation of contaminated soils is a field of technology that has developed and grown recently. Development and use of remediation technologies has progressed and a large number of clean-up alternatives have evolved and improved over the past decade. In addition, the technology developers and environmental service companies have sprung up in the hope of secure a place for their process in the market. Therefore, there has been a remarkable decrease in unit cost for land treatment options. Remediation has become affordable, allowing owners of small- and medium-sized contaminated sites to undertake soil clean-up programs in a more cost–effective manner. However, both site owners and environmental managers confront the challenge of making decisions to select and deploy the most suitable soil remediation technologies to address a variety of problems and, in some cases, satisfy a number of conflicting criteria.

These choices are increasingly more complex because a greater variety of contamination problems are being defined and innovative technologies are becoming available every day as potential (sometimes cheaper and/or more effective) alternatives to existing technologies (*1-3*). Innovative remediation technologies, which lack a long history of full-scale applications, do not have, in some cases, the extensive documentation necessary to make them a standard choice in the engineering/scientific community. However, many innovative technologies have been successfully used at contaminated sites in the United States, Canada, and Europe despite incomplete verification of their overall performances. Some of the technologies were developed in response to hazardous waste problems and some have been adapted from other industrial uses. Only after a technology has been used at many different types of sites, and the results fully documented and assessed, it is commonly considered as a well-established technology.

Decision makers are also asked to integrate information about remedial options and are required to balance information about technology performance with limited budgetary resources and regulatory constraints. In addition, information about the concerns of stakeholders, as well as their meaningful involvement in the larger decision process, influences the ultimate technology selection and deployment decision. Therefore, all involved parties (environmentalist, policy makers, local community representatives, site owners, other stakeholders) need some tools to help them assembling and synthesizing information to respond to these challenges and conflicting issues.

Therefore, this problem has been chosen to develop DARTS in order to perform evaluation and comparison of technologies for environmental remediation. DARTS provides a set of criteria for evaluating technologies to address site-specific clean-up activities, and would accomplish the following tasks:

- To enable users to identify and systematically compare information about innovative and conventional technologies to meet remediation goals, highlighting their strengths and weaknesses
- To establish a structure of technology evaluation and selection process, which simplifies the decision-making and streamlines the variety of factors involved in the remediation process
- To define consistent, qualitative and quantitative indicators for key technical, environmental, economic, and legal criteria that influence selection and deployment of technologies
- To provide documented, reproducible evaluation which can be updated as needed information becomes available
- To provide flexible, multicriteria optimization approach allowing trade-offs among criteria on the basis of contaminant type and site-specific needs
- To enhance communications and help focus dialogue between local community, environmental managers and stakeholders, including regulators and policy makers
- To enable explanation and justification of the choice by offering evidence on the advantages and disadvantage of the possible choices in a concise and consistent way.

- To fasten development of feasibility study of the remedial options
- To provide site owners, environmental managers and other stakeholders with the opportunity to explore alternative options, etc.

Before a treatment technology can be selected for a contaminated site, detailed information about the site and contaminants characteristics must be collected. DARTS uses this information to determine which of the possible remedies will be capable of meeting the clean-up standards set by its users, respecting the previously mentioned constraints (technical, economical, legal, etc.). The following section will further clarify the role of DARTS in supporting remedial actions.

DARTS FUNCTIONALITY

Remedial actions usually involve these main tasks:

- *Site discovery*, preliminary assessment, and site inspection, conducted to quickly determine if there is a contamination problem.
- *Site assessment* that determines the type and extent of contamination
- *Evaluation of clean-up alternatives*, and selection of remediation technology, based on the type and extent of contamination, clean-up time required, physical, and geological site characteristics, available technologies, resource requirements, social acceptance, and compliance with federal and state laws, etc.
- *Site clean-up*, application of selected remediation technique, and
- *Site closure and compliance monitoring*, ensuring that the identified contamination problems have been adequately addressed

DARTS aims at providing a decision support for the evaluation of clean-up alternatives and selection of the best available technology for the site concerned, simultaneously taking into account a number of different technical, economic, social, legal and environmental criteria. Each criterion could be weighted by the panel of experts, environmental managers, technology providers, policy makers, local community representatives, to capture its relative importance in the overall balance.
There are many actors in the decision-making process, which have their own interests and perspectives. For instance, the person(s) responsible for contamination and the owner of the polluted plot of the land can be mainly interested in the financial issues, while the user of the plot and the direct environment, including nearby residents, are mainly interested in health and environmental issues. Another group is composed by representatives of public bodies. They should consider the overall interests, which includes socio-economic and environmental issues.
The aim of DARTS is working with all mentioned actors to perform a preliminary selection of the most efficient remediation technologies, by analyzing simultaneously some key criteria of available remedial techniques. These criteria can be ranked by all involved parties to determine their relative importance for a particular project.
Multicriteria analysis of all these factors determines whether a remediation strategy is a feasible, effective and efficient solution and whether it satisfies all criteria and constraints defined by the user. Depending on the context in which remediation technology assessment and selection is performed, the users can tailor decision strategy balancing out various

effectiveness and efficiency parameters, other criteria and constraints. From the user's point of view, a general algorithm for DARTS analysis is described in Figure 1.

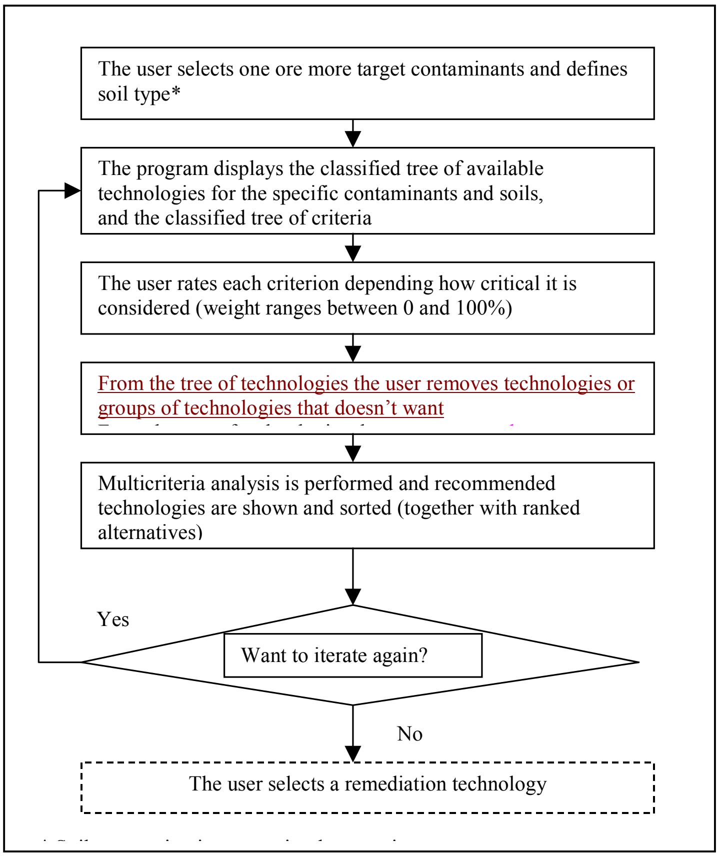


FIGURE 1. General algorithm supported with *DARTS*.

An example of practical approach using DARTS is when applying a soil remediation decision tree (*4*) (Figure 2); in this case, the user is able to analyze and compare subgroups of technologies, or to compare technologies within the same subgroup. The technologies available in the current stage of DARTS are indicated in Figure 2. This approach also applies for groundwater remediation programs, which can be integrated in the remediation decision tree supported with DARTS.

CRITERIA TO ASSESS AND SELECT REMEDIATION TECHNOLOGIES

DARTS' user selects a subset of technologies in which is interested, or uses a full set of technologies and ranked criteria (*6,7*); selects the criteria, preference functions (or use default functions chosen by the DARTS developers) and corresponding weighting factors, defines the contaminant (or a group of contaminants), soil type and then performs a multicriteria analysis.

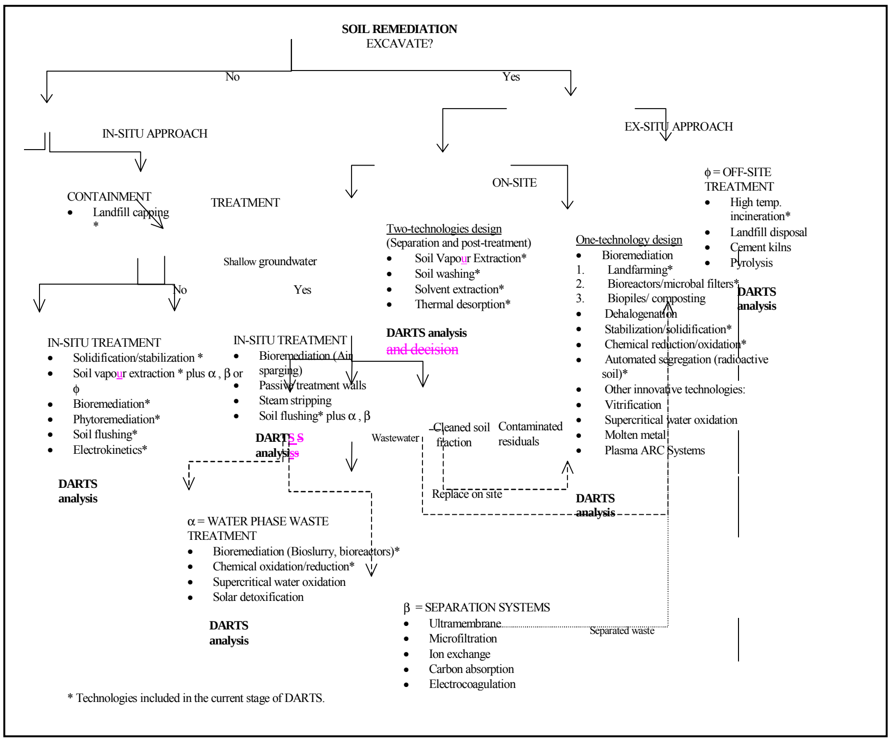


FIGURE 2. Soil remediation decision tree supported with *DARTS*

The criteria included in the current stage of DARTS prototype are applicability, overall cost, minimum achievable concentration, clean-up time required, reliability and maintenance and public acceptability (that varies depending on the country and site location); two more criteria are currently being implemented: by-products/wastestreams post treatment required and decontaminated soil quality. A numerical rating of 1 (= better), 2 (= average) or 3 (= worse) is given to each technology in each category (*6*). These categories are taken from the ratings reported in UN-ECE Compendiums of soil remediation technologies (*6,7*), and are mainly based on the US-EPA's evaluations. The categories are briefly explained below.

Overall cost. Includes design, construction, operation and maintenance costs of the core process that defines each technology. It does not include site preparation or post-treatment costs. Excavation costs of $55/metric ton are assumed for ex situ technologies.

Ratings: 1= Less than $110/metric ton;
2= $110 - $330/metric ton;
3= More than $330/metric ton

Minimum achievable concentration. Refers to the minimum pollutant concentration achievable by the technology.

Ratings: 1= Less than 5 mg/kg soil;
2= 5-50 mg/kg soil; and
3= More than 50 mg/kg soil

Clean-up time required. This refers to a "standard" site of .41 hectare and 3.04 m depth. The soil mass is 18,200 metric tons.

Ratings for ex situ techniques:
- 1= Less than 6 months;
- 2= 6 months -1 year; and
- 3= More than 1 year.

Ratings for in situ techniques:
- 1= Less than 1 year;
- 2= 1-3 years; and
- 3= More than 3 years.

Reliability and maintenance. Refers to the level of complexity of the system or technology, and how easy it is to maintain.

Ratings: 1= High reliability and low maintenance;
2= Average reliability and maintenance; and
3= Low reliability and high maintenance

PUBLIC ACCEPTABILITY

Degree to which the technology is acceptable to the public. This category can, of course, vary widely depending on the country and the level of community involvement.

Ratings: 1= Minimal opposition from the community is likely;
2= Public involvement usually occurs, but the technology is generally accepted;
3= Serious public involvement is likely and the outcome is uncertain.

Other ratable criteria that will be included in the system prototype are: data needs/characterization (refers to the extent of pre-remediation investigations) and safety requirements (refers to the measures required to ensure safety of workers, public and environment).

MULTICRITERIA ANALYSIS ALGORITHM

A multicriteria analysis performed by DARTS is the process during which the relative merits of the remediation alternatives are compared to each other and the most appropriate is selected from among them for site clean-up implementation.

There are a number of fundamental problems when there are multiple objectives. For instance, consider the case where there are a number of decision makers, each with a preference ordering over a number of alternatives. The goal is to choose the ``fair'' alternative that aggregates the preferences of the decision makers. This is an example of multiple criteria decision making (each decision-maker represents one criterion), and those objectives need to balance in a fair way. The situation is even more complicated when there are also multiple and even conflicting criteria like in the DARTS (where for instance, minimizing cost and clean-up time could be conflicting requirements). The decision-maker is asked to specify goals and relative weightings for the different criteria. Relative weightings are used to find most preferred solutions. The weighting can be changed to assess sensitivity of solution or to reflect different opinions.

The explicit consideration of multiple, even conflicting objectives in a decision model has made the area of multiple criteria decision-making (MCDM) very popular among researchers during the last two decades. It is quite conceivable that certain modifications in the existing MCDM procedures provide the long awaited bridge between the important fields of Operations Research and Decision Support Systems. In order to support the decision maker that must solve multicriteria problems, three kinds of methods were essentially considered - aggregation methods using utility functions, interactive methods and outranking methods. In our work, we adopted the last ones, actually a special outranking method, based on extensions of the notion of criterion (5) (PROMETHEE I, providing a partial preorder, and PROMETHEE II, providing a total preorder on the set of possible decisions).

These extended criteria can be easily defined by the decision maker, because they represent the natural notion of intensity of preference, and the parameters to be fixed (maximum 2) have a real world meaning. The extension is based on the introduction of a preference function, giving the preference of the decision maker for an action *a* with regard to *b*. This function is defined separately for each criterion, where its value is between 0 and 1 (meaning a range between 0 and 100%), within the same defined criterion. The smaller the function, the greater the indifference of the decision maker; the closer to one, the greater his preference. In case of strict preference, the preference function is 1. Numerous practical applications of the PROMETHEE method have shown that it is very easily accepted and understood by the practitioners, being the easiest approach for solving a multicriteria problem by considering simultaneously extended criteria and outranking relations.

A preference function, $P_h(a, b)$, is usually presented by a function $p(x)$:

$$p(x): x \to [0, 1] \text{ and } x = f(a) - f(b),$$

where $f(a)$ and $f(b)$ represent the values of a particular criterion, *h*, for actions *a* and *b* respectively.

Using a preference index, $\pi(a, b)$, we can determine the preference for *a* with regard to *b* over all criteria:

$$\pi(a, b) = \frac{1}{\sum_{h=1}^{k} W_h} \sum_{h=1}^{k} W_h P_h(a, b)$$

where *k* represents the number of criteria, W_h is a weight for the criterion *h*, and $P_h(a, b)$ is the preference function for the criterion *h*.

A *valued outranking graph* consists of nodes represented by actions and arcs, where each arc (a, b) has a value $\pi(a, b)$. When obtained, the *valued outranking graph* offers a decision-maker means for determining a partial preorder (PROMETHEE I), or a total preorder (PROMETHEE II).

In order to rank the actions by a partial preorder, we must evaluate the outgoing flow:

$$\phi^+(a) = \sum_{x \in K} \pi(a, x),$$

where *K* is the set of all actions, and the incoming flow:

$$\phi^-(a) = \sum_{x \in K} \pi(x, a).$$

The outgoing flow $\phi^{+}(a)$ describes the degree to which *a* dominates the other actions in K, while the incoming flow $\phi^{-}(a)$ represents the degree to which *a* is dominated. Using the outgoing and incoming flows, the two total preorders (P^{+}, I^{+}), and (P^{-}, I^{-}) can be defined, such that:

$$\begin{aligned} &a\,P^{+}\,b \quad \text{if} \quad \phi^{+}(a) > \phi^{+}(b),\\ &a\,P^{-}\,b \quad \text{if} \quad \phi^{-}(a) > \phi^{-}(b); \end{aligned}$$

$$\begin{aligned} &a\,I^{+}\,b \quad \text{if} \quad \phi^{+}(a) = \phi^{+}(b),\\ &a\,I^{-}\,b \quad \text{if} \quad \phi^{-}(a) = \phi^{-}(b). \end{aligned}$$

Then the partial preorder ($P^{(1)}$, $I^{(1)}$, R) can be determined by considering their intersections:

$$\begin{cases} a \text{ outranks } b\ (a\,P^{(1)}\,b) & \text{if } \begin{cases} a\,P^{+}b \text{ and } a\,P^{-}\,b,\\ a\,P^{+}b \text{ and } a\,I^{-}\,b,\\ a\,I^{+}b \text{ and } a\,P^{-}\,b, \end{cases}\\ a \text{ is indifferent to } b\ (a\,I^{(1)}\,b) & \text{if } \ a\,I^{+}b \text{ and } a\,I^{-}\,b,\\ a \text{ and } b \text{ are incomparable } (a\,R\,b) & \text{otherwise.} \end{cases}$$

The net-flow: $\phi(a) = \phi^{+}(a) - \phi^{-}(a)$

is used to rank the alternatives by a total preorder ($P^{(2)}$, $I^{(2)}$):

$$\begin{cases} a \text{ outranks } b\ (a\,P^{(2)}\,b) & \text{if } \ \phi(a) > \phi(b),\\ a \text{ is indifferent to } b\ (a\,I^{(2)}\,b) & \text{if } \ \phi(a) = \phi(b). \end{cases}$$

DARTS EXPERIMENTAL PROTOTYPE

A laboratory prototype of DARTS has been developed as JAVA application, using Symantec Visual Café dbDE development environment.

The DARTS presents its users with a variety of configuration and input parameters from which to choose. Several are mandatory (such as identifying technologies to be evaluated), but there are many that the user can choose to leave blank or use the supplied default values. This way, the user decides how to tailor the analysis to satisfy specific needs.

Prototype configuration and data entry process involves several tasks:

- Entering available technologies and their descriptions
- Entering criteria to be considered simultaneously
- Setting values of chosen criteria and selecting the type of preference function for each criterion

The application's main window (Figure 3) consists of the current state of configuration, and a few dialogs for data entry purposes. It is connected to the database that contains previously entered information on available technologies and selection criteria; database should be registered by the user and/or software administrator. An application window consists of the following sections:

- *Technologies* tree structure
- Buttons for manipulating nodes of the *technologies* tree
- *Criteria* tree structure
- Buttons for manipulating nodes of the *criteria* tree
- Button for setting values of the selected criteria
- Button for starting multicriteria decision making process
- Button for selecting contaminants for multicriteria decision making process

A dialogue box requesting the user to select the technologies to be simultaneously evaluated and compared with one another is shown in Figure 3.

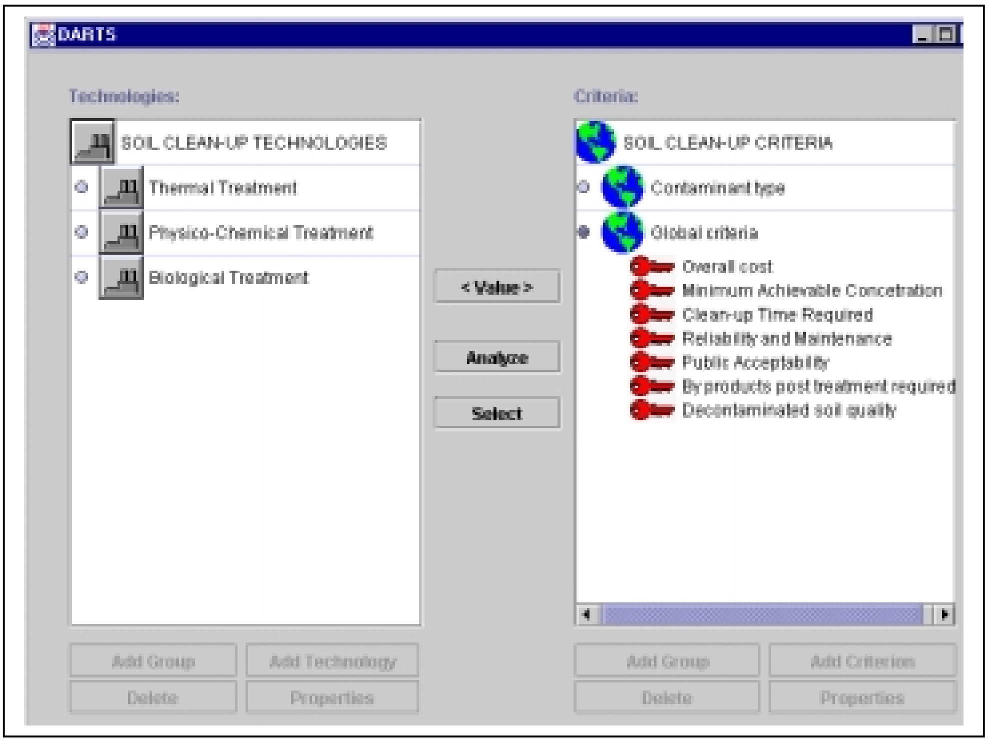


FIGURE 3. Main application window

A dialogue box *Technology Properties* (Figure 4) is used for entering and updating information on particular technology. It consists from a few text fields and standard OK and Cancel buttons. Main fields are for technology identification code, name and description. Three other text fields are disabled, and they are used for presentation of multicriteria analysis results. Radio buttons *On* and *Off* are used for including/excluding selected technology in multicriteria analysis.

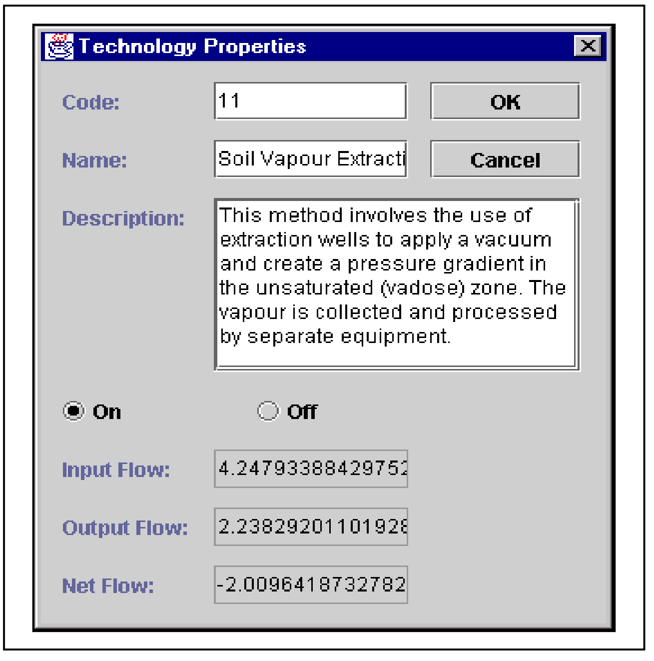


FIGURE 4. Technology properties dialogue box

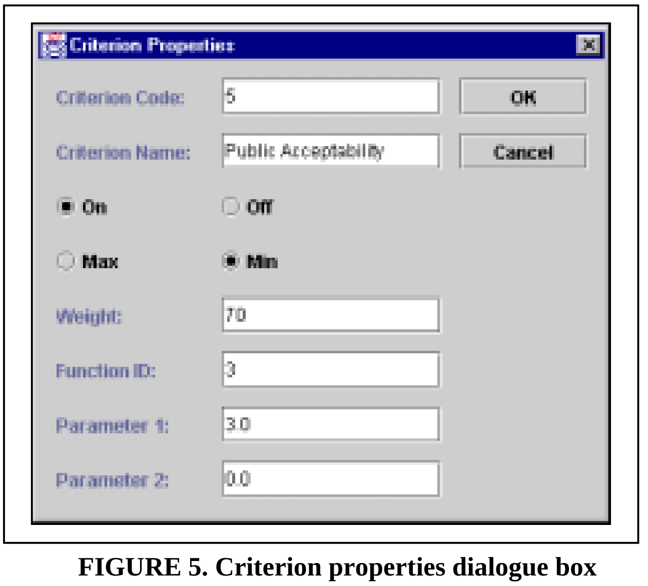


FIGURE 5. Criterion properties dialogue box

A dialogue box *Criterion Properties* (Figure 5) is used for entering and updating attributes of particular criterion. It consists of several text fields, four radio buttons, and standard OK and Cancel buttons. Main fields are for criterion identification code, name, weighting factor, function ID, i.e. he identification code of the selected preference function for the criterion, and its parameters. Radio buttons *On* and *Off* are used for including/excluding selected criterion in multicriteria analysis. *Min* and *Max* radio buttons show whether selected criterion is maximized or minimized.

A dialogue box *Criterion-Technology Properties* (Figure 6) is used for entering and updating a value of the specific criterion for selected technology.

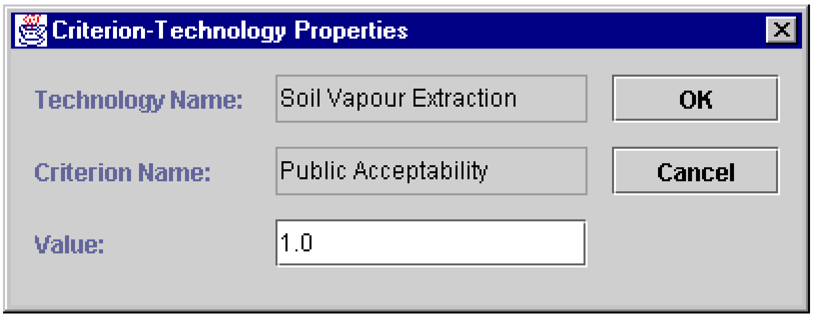


FIGURE 6. Criterion-Technology properties dialog box

A window *Technology Criteria Overview* (Figure 7) is used to overview the values of all selected criteria for particular technology.

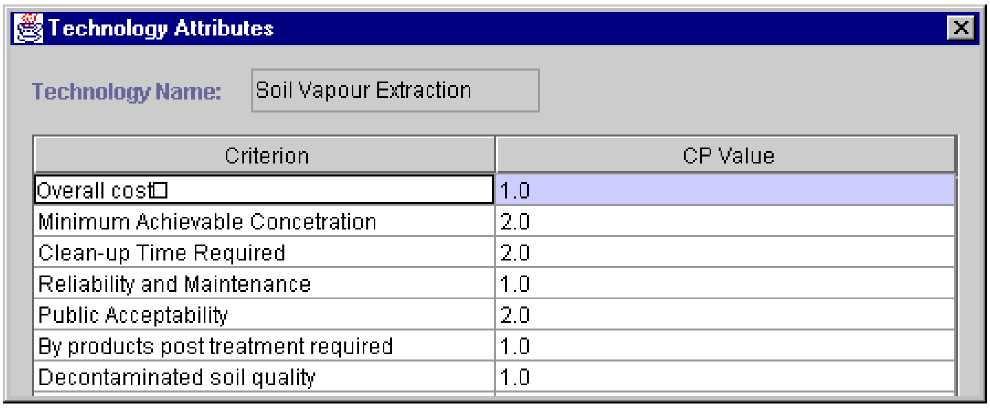
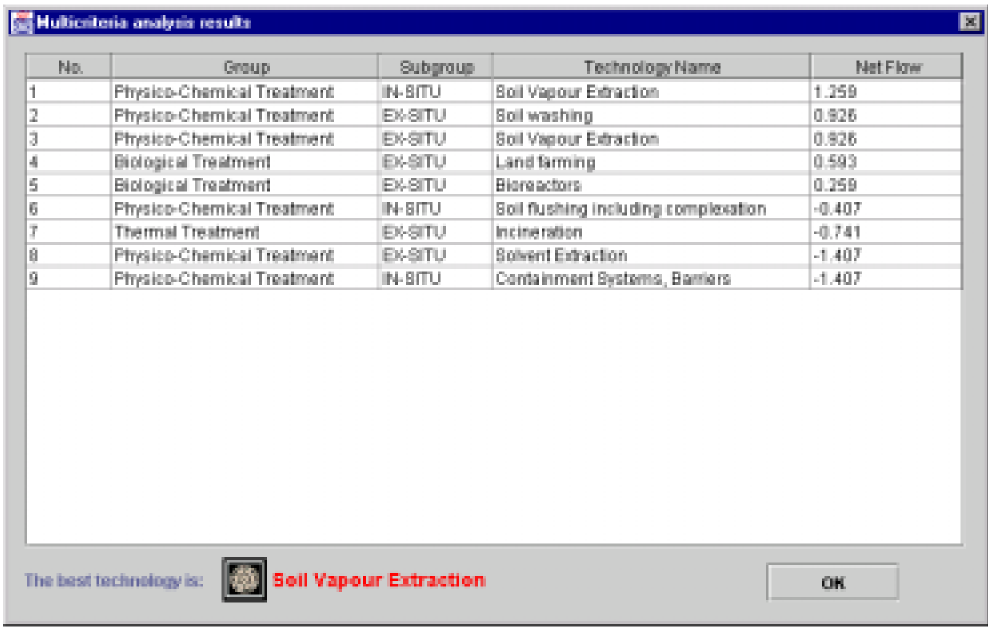


FIGURE 7. Complete Technology criteria overview

A window *Multicriteria analysis results* (Figure 7) is used for the presentation of the results of multicriteria analysis process. The best technology (with maximum net flow) is emphasized using red color. Here, the decision has been made upon the arbitrary choice of input parameters, so the results must not be taken seriously.



Multicriteria analysis results

No.	Group	Subgroup	Technology Name	Net Flow
1	Physico-Chemical Treatment	IN-SITU	Soil Vapour Extraction	1.259
2	Physico-Chemical Treatment	EX-SITU	Soil washing	0.926
3	Physico-Chemical Treatment	EX-SITU	Soil Vapour Extraction	0.926
4	Biological Treatment	EX-SITU	Land farming	0.593
5	Biological Treatment	EX-SITU	Bioreactors	0.259
6	Physico-Chemical Treatment	IN-SITU	Soil flushing including complexation	-0.407
7	Thermal Treatment	EX-SITU	Incineration	-0.741
8	Physico-Chemical Treatment	EX-SITU	Solvent Extraction	-1.407
9	Physico-Chemical Treatment	IN-SITU	Containment Systems, Barriers	-1.407

The best technology is: Soil Vapour Extraction

OK

FIGURE 8. Multi-Criteria analysis results

Please note that the above results are obtained for arbitrary set of contaminants, selection criteria and their values and preference functions. Soil Vapor Extraction Technology has been recommended as the best choice for this random selection of input parameters. We deliberately avoided presentation of the real world, interactive decision-making session with DARTS.

DARTS TESTING

Several tests have been made in order to verify the accuracy of DARTS results against reported real cases. Some criteria considered by Brownfields Technology Support Center (*8*) for selecting and recommending remediation technologies for the Union Pacific Railroad Site (UPRS), Clinton, Iowa, are presented in Table1.
In the first step, the conditions measured in the study case were translated to parameters in DARTS, which are presented in Table 2. In order to make the DARTS analysis results comparable to those of Brownfields, the analysis was separately performed for each group of contaminants (VOCs and heavy metals).
DARTS results are presented and ranked in Table 3, and are compared against recommendations made by Brownfields. Most of the technologies proposed by DARTS are included in Brownfields recommendations, only some variations of Bioremediation (Landfarming and Bioreactors) do not match since these technologies are grouped in DARTS as Bioremediation. Soil flushing is ranked on the last place, because its low ability to clean until acceptable levels which DARTS considers as more than 50 mg/kg soil. UPRS case requires between 5-50 mg/kg for benzene and less than 5 mg/kg.

Criteria / Parameter	Description	
Applicability	VOCs and Petroleum hydrocarbons in soil and groundwater	Arsenic in soil Arsenic and lead in groundwater
Risk-based clean-up level *	22 ppm (benzene in soil) 0.36 ppb (benzene in groundw.)	3.8 ppm (arsenic in soil) 0.045 ppm (arsenic in groundw.) 50 ppm (lead in groundw.)
Clean-up time required	< 1 year	< 1 year
Cleaned soil availability	To be used as a light industrial and/or commercial retail area	

TABLE 1. Parameters obtained from Environmental Assessments performed on UPR Site, Clinton, Iowa

Criteria / Parameter	Description Weight (%)	
Applicability	VOCs / Hydrocarbons 100%	Heavy metals 100%
Minimum achievable concentration	5 – 50 mg/kg (benzene)+ >50 mg/kg (other hydrocarbons) 30 – 50%	< 5 mg/kg (arsenic) 100%
Clean-up time required	< 1 year 50%	< 1 year 50%

+Benzene concentrations detected during Environmental Assessments were always below 22 ppm.

TABLE 2. Criteria translated to parameters in DARTS.

Some biological remediation technologies (bioremediation *in-situ* and landfarming) are also classified on the last places because of their high times required to complete the clean-up (usually more than 1 year). In the UPRS case, it was proposed a restriction of time: less than one year. If the overall cost were considered, the bioremediation technologies would increase the ranked level because of its lower cost compared to other thermal or physical-chemical technologies.

Coming to the end, the selection of the remediation technology is a matter of balancing out environmental achievements against reasonable cost. Different technologies have different performance, and this holds for technical and financial aspects as well as for environmental aspects. The aim of DARTS is to help integrating all these aspects and make a comparative analysis of the best available technologies, taking into account site-specific requirements, and various criteria set by environmental managers, policy makers, site owners and other stakeholders.

Brownfields recommendation	DARTS Multicriteria Analysis results*	DARTS ranked list
VOCs / Hydrocarbons		
Air sparging	Thermal desorption	1.302
Bioremediation (ex-situ)	Chemical treatment	1.036
Bioslurry (ex-situ) †	Thermally enhanced soil vapor extraction	1.036
Bioremediation groundw. (in-situ)	Soil Vapor Extraction/ Air sparging (in-situ)	0.770
Bioventing †	Bioreactors	0.770
Chemical treatment	Soil Vapor Extraction (ex-situ)	0.770
Dual phase extraction †	Solvent extraction	0.504
Soil flushing	Land farming	0.504
Soil vapor extraction	Bioremediation (in-situ)	0.504
Thermal desorption	Soil flushing	0.238
Heavy metals		
Chemical treatment	Chemical treatment	1.232
Phytoremediation	Phytoremediation	0.700
Soil flushing	Solidification/stabilization (ex or in-situ)	0.700
Solidification/stabilization	Solvent extraction	0.700
Solvent extraction	Containment systems / Barriers	0.168
	Soil flushing	0.168

* "Overall cost" not included as criteria. † Technologies not available in current DARTS prototype.

TABLE 3. Comparison of recommendations made by Brownfields and those obtained with DARTS.

Internet accessible version of DARTS is currently under construction. The client-server architecture adopted for Internet version, assumes that all the analysis and database administration is done at the server side, while a light client (i.e. a distant user) needs only a standard Web browser and proper authorization to access and use the DARTS.

ACKNOWLEDGMENTS

The authors wish to express their gratitude to Vladimir Simeunović for his precious contribution during the development of the experimental prototype of the software. The authors also thank Branislav Opačić for his support during the project.

SUPPORT INFORMATION AVAILABLE

Information about conventional and innovative remediation technologies is available free of charge via the Internet at http://www.environment.gov.au/epg/swm/swtt/contents.html, http://www.frtr.gov and http://www.epareachit.com.

The Compendium of soil clean-up technologies and soil remediation companies, edited by ICS-UNIDO and UNECE, offers three sections: soil clean-up technologies and criteria to assess the options, list of web sites describing remediation technologies and a worldwide directory of companies dealing with soil remediation.

Additional information about Multicriteria Decision Making (MCDM) Methodologies can be found in:

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