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THESIS SUBJECT	**COMPARING OPTIONS FOR THE MANAGEMENT OF CONTAMINATED LAND ON NUCLEAR AND DEFENCE SITES IN THE UK** **Review and Assessment of Options Comparison Methodologies**
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Executive Summary

Decision makers face several problems in environmental projects in that environmental decisions are often sophisticated and involve many different stakeholders with different priorities or objectives. This is because of the limited availability of guidance on judging the relative importance of information from each source. In addition, decision makers, in general do not receive structured information about the stakeholder preferences and receive information in different forms. Therefore, decision makers are not provided with necessary information to enable their choice between identified project options.

The contaminated land situations likely to be considered are wide and varied; however, they can be classified as simple, intermediate and complicated situations. A simple situation can be described as a small patch of contaminated land on a controlled nuclear or defence site with interest from only a few stakeholders. An intermediate situation can be described as large area of contaminated land, for which an implementation technology needs to be identified, with the local stakeholder interest. A complicated situation can be described as a whole site, with interest from many stakeholders.

In the late 1990s a project was initiated to develop guidance on managing contaminated land on nuclear and defence sites. It was named “SAFEGROUNDS” (***SAF***ety and ***E***nvironmental ***G***uidance for the ***R***emediation ***o***f ***U***K ***N***uclear and ***D***efence ***S***ites) and has been managed to the present day by CIRIA (the Construction Industry Research and Information Association). Following feasibility studies, SAFEGROUNDS produced some initial guidance to support good practice in the health, safety and environmental aspects of managing contaminated land.

In 2002 a main guidance document was produced, entitled Good Practice Guidance for the Management of Contaminated Land on Nuclear and Defence Sites (known as the Land Management Guidance). This document is subject to regular review and update to reflect not just changing policy and regulatory drivers but also developments in good practice. Therefore, a programme to develop new guidance was initiated in 2006. In the period from autumn 2006 to summer 2008 SAFEGROUNDS will be revising all its existing guidance documents and adding some new ones.

The aim of the thesis is to input into an important document in the SAFEGROUNDS suite, the Options Comparison Guide. This report acts as a supporting document to the Option Comparison Guide, and provides a basis for the methods presented in the guide.

Multi criteria techniques incorporate a wide variety of approaches ranging from the highly sophisticated to simple rating systems. The aim of these approaches is to set up a framework in order to evaluate the impact of making a decision as well as to simplify the decision into elements. The most important advantage of multiple criteria analysis (MCA) over the informal judgment is its capacity to simplify complex situations. Without using structured approaches decision makers cannot take account of the totality of relevant information in their judgment. MCA breaks down the components of complex situations, and provides a method by which the decision makers can gain a good understanding of the elements of the decision making process. In addition, it is a useful negotiation tool for debates among decision makers. Therefore, using MCA techniques provides strong foundations to decision makers to make structured and transparent decisions in the way required in environmental decision making.

The main approach adopted throughout the thesis is MCA. Different MCA methods are compared in terms of deciding which method would be the most efficient one for the contaminated land management. Among them, direct evaluation of performance matrix, dominance analysis, linear additive methods, multiple criteria decision analysis, even swaps, analytical hierarchy process and non compensatory methods are suggested. These methods provide the most meaningful approaches in terms of option comparison of contaminated land management. They are relatively easy to apply, provide transparency and are open to a wide of users. This allows every stakeholder to participate in the decision process.

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I. Introduction

Environmental decisions are often complex and multifaceted and involve many different stakeholders with different priorities or objectives. There are several problems facing decision makers in environmental management projects. The first problem is the limited availability of guidance on judging the relative importance of information from each source. Secondly decision makers receive information from different forms. For instance, socio-economic analyses contain more qualitative judgment whereas the results of modelling and monitoring studies incorporate quantitative information. Thirdly, decision makers mostly do not receive structured information about stakeholder preferences. Even if they receive this information, the way of dealing with it could be subjective and decision process might not be reliable and fair. Therefore, there is a risk that decision makers can not successfully identify all possible options and they are not provided with necessary information to inform the choice between identified project options, that is to say "*they are prevented from identifying all plausible alternatives and from making full use of all available and necessary information in choosing between identified project alternatives*"[1].

SAFety and **E**nvironmental **G**uidance for the **R**emediation **o**f **U**K **N**uclear and **D**efence **S**ites (SAFEGROUNDS) was developed in the late 1990s to provide guidance on the management of contaminated land on nuclear and defence sites where radioactive contamination might be present. It is run by an independent Project Steering Group (including NGO representatives) and is funded by a range of bodies including industry and Government. Its advice is very important because contaminated land on such sites is a major issue for local stakeholders. The associated clean-up may cost very large sums of money, especially in relation to decommissioning nuclear sites (many millions of pounds). Decision-making therefore needs to be undertaken in an open, inclusive and auditable manner, so the outcome is robust and takes account of all views.

The existing "Land Management Guidance" which was produced by SAFEGROUNDS sets out an overarching approach. This was developed with input from a wide range of stakeholders. However, it is not particularly specific, and there has been a recognition that more detailed advice on particular options comparison methods would be very valuable. This is in part because the guidance is intended to apply across a very wide range of situations:

- ▲ from deciding what to do about a small patch of contamination in the corner of an established nuclear site; to
- ▲ deciding on a strategy for the clean-up of contaminated land a major nuclear facility, which might take decades and cost hundreds of millions of pounds.

Therefore, different levels of detail are relevant to such differing situations, and that the extent of stakeholder engagement can vary considerably. However, there is little guidance to indicate the range of options comparison methods that can be used (from simple to complex) and how they might be applied.

The aim of the thesis is to input into an important document for the UK nuclear and defence industry, to be produced as part of the "SAFEGROUNDS" programme, which will provide good practice guidance on dealing with such situations. Due to the fact that Quintessa Limited will be responsible for this document, the final report will act as a supporting document in the SAFEGROUNDS suite of documents that is currently under revision.

As known, decision support methods help make the decision making processes transparent, documented, reproducible, robust and provide a coherent framework to explore the options available. Decision analysis processes such as Multi Criteria Decision Analysis (MCDA) have been developed and applied to achieve these objectives. In a manual developed for the Department of the Environment,

[1] Application of Multicriteria Decision Analysis in Environmental Decision Making; Gregory A. Kiker, Todd S. Bridges, Arun Varghese, Thomas P. Seager and Igor Linkov; Integrated Environmental Assessment and Management Vol. 1 Number 2 pp. 95-108

Transport and the Regions (DETR), MCDA is defined as "both an approach and a set of techniques, with the goal of providing an overall ordering of options, from the most preferred to the least preferred option." MCDA is a form of Multiple Criteria Analysis (MCA) and Multi criteria techniques incorporate a wide variety of approaches ranging from the highly sophisticated to the simple rating systems. The aim of these approaches is to set up a framework in order to evaluate the impact of making a decision as well as simplify the decision into elements. The most important advantage of multiple criteria analysis over informal judgment is its capacity to simplify complex situations. Without using structured approaches decision makers cannot take account of the totality of relevant information into their judgment. MCA breaks down the components of complex situations, and provides a method by which decision makers can gain a good understanding of the elements of decision making process. In addition, it is a useful negotiation tool for debates among decision makers. Therefore, using MCA techniques definitely provides with strong foundations to decision makers to make structured and transparent decisions.

The main approach adopted throughout the report is MCA. Different MCA methods are compared in terms of deciding which method would be the most appropriate for contaminated land management. Therefore, the report provides a review of a range of systematic options comparison methods and a description of how they might be applied in the context of deciding what to do with radioactive and non-radioactive contamination in land on nuclear and defence sites in the UK. Using the proposed approaches the different stakeholders will be able to compare and contrast different procedures.

The work within the report has been organized as follows:

Chapter 2 gives the preliminary information on radioactively contaminated lands, the options considered by decision makers for these kinds of situations and discusses the scope of situations that need to be considered.

Chapter 3 presents an overview of multi-criteria analysis and states its advantages over informal judgments, and briefly explains the stages of MCA.

Chapter 4 includes a survey of multi-criteria methods. The methods are briefly explained and their strengths and weaknesses are discussed.

Chapter 5 evaluates the suitability of these methods in the context of contaminated land management. The most central of the MCA methods are described and their appropriateness for the option comparisons is discussed.

Chapter 6 gives a brief conclusion of the report.

Chapter 7 gives the reflections about the findings.

II. Contaminated Land on Nuclear and Defence Sites

II. 1. Contaminated Land

The term contaminated land covers a wide range of situations where land is contaminated in some way. In the SAFEGROUNDS Good Practice Guidance contaminated land is defined as follows: “Any land on or under which radioactive or non-radioactive contaminants are suspected to be present at consideration levels above the natural and artificial background concentration levels that are typical of the location of the site”.

The Word Health Organisation defines contaminated land as land containing a substance or substances in quantities or concentrations potentially harmful to human health, animals, plants, buildings, building services or other environmental receptors. The term land includes any structures, surface material, top soil, subsoils, surface water, groundwater and aquifers.

In short, when substances are present in land where they would not normally be found, the land may be considered to be contaminated. However, there are a wide variety of man-made substances in the environment, and it is necessary to define what is considered to be “contamination”. For example, land amended with fertilizers is not generally considered to be contaminated, but water in which high concentrations of nitrogen from the fertilizers has accumulated may well be considered to be contaminated. The definition of “contamination” therefore usually relates to the potential for substances to harm people or the environment. In UK legislation, Part IIA of the Environmental Protection Act defines contaminated land as that in which a “pollutant linkage” (a pathway from a source of contamination to environmental receptor[2]) exists and that the pollutant linkage:

- ▲ is resulting in significant harm being caused to the receptor; or
- ▲ presents a significant possibility of significant harm being caused to that receptor.

There are thousands of sites in the UK that have been classified as contaminated. The contamination is often as a result of industrial processes or activities that have now ceased. There is increasing pressure to reuse this land and so appropriate ways of managing it (which may or may not involve clean-up by some method) need to be considered.

Figure 2.1: Investigating Some Typical Contaminated Land

[2] The water environment itself may also be considered to constitute a receptor.

Most of these contaminated sites feature chemical contaminants. There is a well established regime for dealing with such circumstances and determining an appropriate regime for managing the land. However, in a few cases radioactive contaminants are present, or suspected. The nature of radioactive contaminants is such that they can result in harm by different pathways than chemical contaminants. Most notably, the contaminants do not need to enter an organism to cause harm – radioactive materials can irradiate organisms at a distance. Another important feature is that the very low concentrations of some radionuclides may pose a hazard. Finally, it must be noted that specific regulatory regimes apply to radioactive substances (the Radioactive Substances Act, 1993) and the protection of human health from radiation (the Ionizing Radiation Regulations, 1999). For these reasons, radioactive contamination merits specific consideration.

II. 2. Radioactively Contaminated Land

Radioactive contamination has arisen from various sources, as radioactive substances have been used in industry as well as in relation to nuclear power and defence. Non-nuclear industries have used radioactive substances specifically for their radioactive properties (e.g. radium-based paints), for other properties (e.g. thorium oxide in gas mantles), or produced them as a by-product of other processes (e.g. smelting tin). However, the widest use of radioactive materials has been in the nuclear power and defence industries which in the UK have been in existence since the late 1940s.

II.2.1 Nuclear Power

In the early years of the development of nuclear power knowledge of the biological hazards of radioactivity was limited. Whilst controls existed, the levels of radioactivity that were tolerated were substantially higher than today. Consequently, incidents of contamination that occurred through leaks, spills and discharges were often not regarded as a major issue. Since regulations concerning radioactive substances came into force in the 1960s greater controls have been exercised. In recent decades, knowledge and experience has increased and regimes for the control and safe management of radioactive materials have strengthened, whilst limits for exposure have been reduced. However, there remains the possibility for accidental and unexpected contamination incidents to occur or be found.

On nuclear sites historic contamination has generally been identified, managed and controlled in a manner that prevents any hazards to the workers. The regime can rely upon active controls such as the prevention of access to contaminated areas. However, for sites that are now undergoing decommissioning, there is a need to consider what management regime is appropriate for the contamination in the future, when some or all parts of the site may be returned to public use. Many sites are considering decommissioning end points that would return the land to public use, in which case it will need further restoration to ensure safety.

II.2.2 Defence

In the early years of the development of the UK's independent nuclear deterrent, work was focused primarily upon obtaining the raw materials for weapons. This, along with limited knowledge of radiological hazards, resulted in radioactive contamination occurring on defence sites.

Defence sites have voluntarily worked to the same standards imposed by the regulatory regime for nuclear sites for several decades, and many are now fully regulated. However there remains a legacy of historic contamination that, whilst it remains safely under control on operating sites, will require further assessment and potentially remediation if those sites are to be sold.

Another specific issue of interest in relation to the defence legacy of radioactive contamination is associated with the widespread use of radium in during the Second World War to illuminate dials, gauges, and even mark runways. Radium is a particularly problematic radionuclide as it is both relatively hazardous and also has a long half-life (of 1,600 years). In the post war period, during the decommissioning of airfields in particular, substantial quantities of radium contaminated materials were disposed of or burned leading to contamination of a substantial number of sites. Many of these sites have significant value, being located in southern England.

II. 3. Managing Contaminated Land

Identified contaminated land on nuclear and defence sites is managed in a safe manner consistent with the expectations of regulators. However, there is a need to periodically review the strategies to ensure that they remain appropriate. Furthermore, many sites are now moving towards decommissioning and environmental restoration, with an ultimate endpoint that might involve returning some or all of the land to the public. In these circumstances, the regime for managing the contamination will almost certainly need to be changed, as the regulatory controls and security that go with nuclear and defence sites may no longer be available to ensure people's safety.

II.3.1 Options for Contaminated Land

In determining, or reviewing, a management strategy it is necessary to take account of the characteristics of contamination and its context, then consider the options for its management. The options for dealing with contaminated land are in essence quite simple, and are:

- ▲ do nothing (if the hazard can be shown to be limited);
- ▲ remove some or all of the contamination, and then dispose of it in purpose-built facilities for radioactive waste;
- ▲ immobilise some or all the contamination in the ground;
- ▲ further isolate the contamination by the addition of barriers; and/or
- ▲ adopt a mixture of the above options

Within these broad approaches there is a wide range of technologies available. The range of options to consider is therefore potentially significant.

The choice of an option has always been driven by consideration of factors such as safety performance, environmental effects, reliability, regulatory issues and costs. However, until relatively recently (the last decade or so) the process of identifying and assessing options against these criteria has not necessarily been recorded in a transparent manner. Recognising that it is important to engage with people on issues such as the management of environmental contamination, as well as recognising the benefits of systematic approaches to assessing options, has led in the last decade to the routine application of formalised options comparison methods. Most notably, the "Best Practicable Environmental Option" (BPEO) approach has become widely used.

Figure 2.2: Remediation of Contaminated Land

II.3.2 SAFEGROUNDS

In the late 1990s a project was initiated to develop guidance on managing contaminated land on nuclear and defence sites. It was named "SAFEGROUNDS" (**SAF**ety and **E**nvironmental **G**uidance for the **R**emediation **o**f **U**K **N**uclear and **D**efence **S**ites) and has been managed to the present day by CIRIA (the Construction Industry Research and Information Association). SAFEGROUNDS is funded by a range of industry bodies and its work is steered by a Project Steering Group that includes industry, regulators and NGOs.

The SAFEGROUNDS mission statement is:

> *"A forum for developing and disseminating good practice guidance on the management of radioactively and chemically contaminated land on nuclear and defence sites in the UK."*

Following feasibility studies, SAFEGROUNDS produced some initial guidance to support good practice in the health, safety and environmental aspects of managing contaminated land. The guidance is developed primarily for site owners, site operators and their contractors. It is also addressed to regulators and groups within the public. It is developed though consultation with all these bodies.

In 2002 a main guidance document was produced, entitled Good Practice Guidance for the Management of Contaminated Land on Nuclear and Defence Sites (known as the Land Management Guidance or LMG). It is a framework for land management and it is underpinned by five key principles that were debated and agreed through independently facilitated stakeholder workshops.

The documents are subject to regular review and update to reflect not just changing policy and regulatory drivers but also developments in good practice. Therefore, a programme to develop new guidance was initiated in 2006. In the period from autumn 2006 to summer 2008 SAFEGROUNDS will be revising all its existing guidance documents and adding some new ones. The guidance documents currently under review or development include:

- the second version of the primary SAFEGROUNDS Land Management Guidance (LMGv2);
- a new citizens' guide to the management of contaminated land;
- a new guidance document on comparisons of options for the management of contaminated land, to support LMGv2;
- a revised guidance document on site characterisation, to support LMGv2.

As stated in the introductory section, the aim of this report is to provide supporting information to the new guide on the comparison of land management options.

III. An Overview of Multi-Criteria Analysis

This part of the report presents the MCA concept. It introduces the concepts, gives the advantages of using an MCA method and briefly explains the stages of MCA.

III. 1. Background and Introduction

Multi-criteria techniques are tools which aim to aid problem solving. They are, in fact, a way of representing the preferences of a decision maker to explicitly come up with a choice between options which involve a number of conflicting objectives.

The multi-criteria approach examines how all the relevant aspects of a problem are assessed and traded off by decision-makers. Essentially it is a top-down exercise, based on decision-makers' perceptions of how a decision can be decomposed into trade-offs between objectives.

Multi criteria techniques incorporate a wide variety of approaches ranging from the highly sophisticated to simple rating systems. The aim of these approaches is to set up a framework in order to evaluate the impact of making a decision as well as simplify the decision into elements. There are usually three steps to transform subjective decision making into an objective and transparent evaluative model. These are as follows:

a. establishing the options,
b. evaluating performance of information for criteria by assessing the value or utility of the options, and
c. comparing the trade-offs between the criteria to solve the problem.

III. 2. Trade-Offs in Decision Making

In making a decision, a decision maker has to take into consideration all the relevant costs and benefits to ensure he makes a sound decision which addresses all concerns. The decision maker's preferred option should be the one that comes closest to meeting the decision maker's objectives. However, in practice, it is unlikely that any one option performs best against all objectives and can be clearly preferred in that each of them shows different advantages and disadvantages. Therefore, it is a complex problem to describe the balance between objectives and come up with the best solution.

In order to solve this complexity, trade-offs between objectives should be determined. This implies that the decision maker must consider how much one aspect must be given up to achieve another. It is very important to make trade offs explicit so that one can be sure that all concerns are addressed. In addition, the approach should be structured transparently so that the reasons behind the decision are clear. As mentioned above, using multi-criteria techniques help decision makers reach efficient decisions by increasing the communication when there are a lot of conflicting objectives.

III. 3. Advantages of MCA over Informal Judgment

MCA is a tool that has been developed for complex multi criteria problems within decision making. MCA methodologies can incorporate qualitative as well as quantitative aspects of the problems in the decision making process.

The most important advantage of MCA is its capacity to simplify complex situations. Without using structured approaches decision makers cannot take account of the totality of relevant information into their judgment (beyond a certain limited number of criteria). MCA breaks down the components of complex situations, and tries to find a solution in a transparent way so that the decision makers will have a good understanding of the contributing elements of the decision.

In addition, it is a useful negotiation tool for debates among decision makers. That is why MCA offers very strong tools to decision makers for both complex issues and conflicting situations. DETR multi-criteria analysis manual states the advantages of MCA over informal judgment unsupported by analysis. These are as follows:

⇒ *It is open and explicit;*
⇒ *The choice of objectives and criteria that any decision making group may make are open to analysis and to change if they are felt to be inappropriate;*

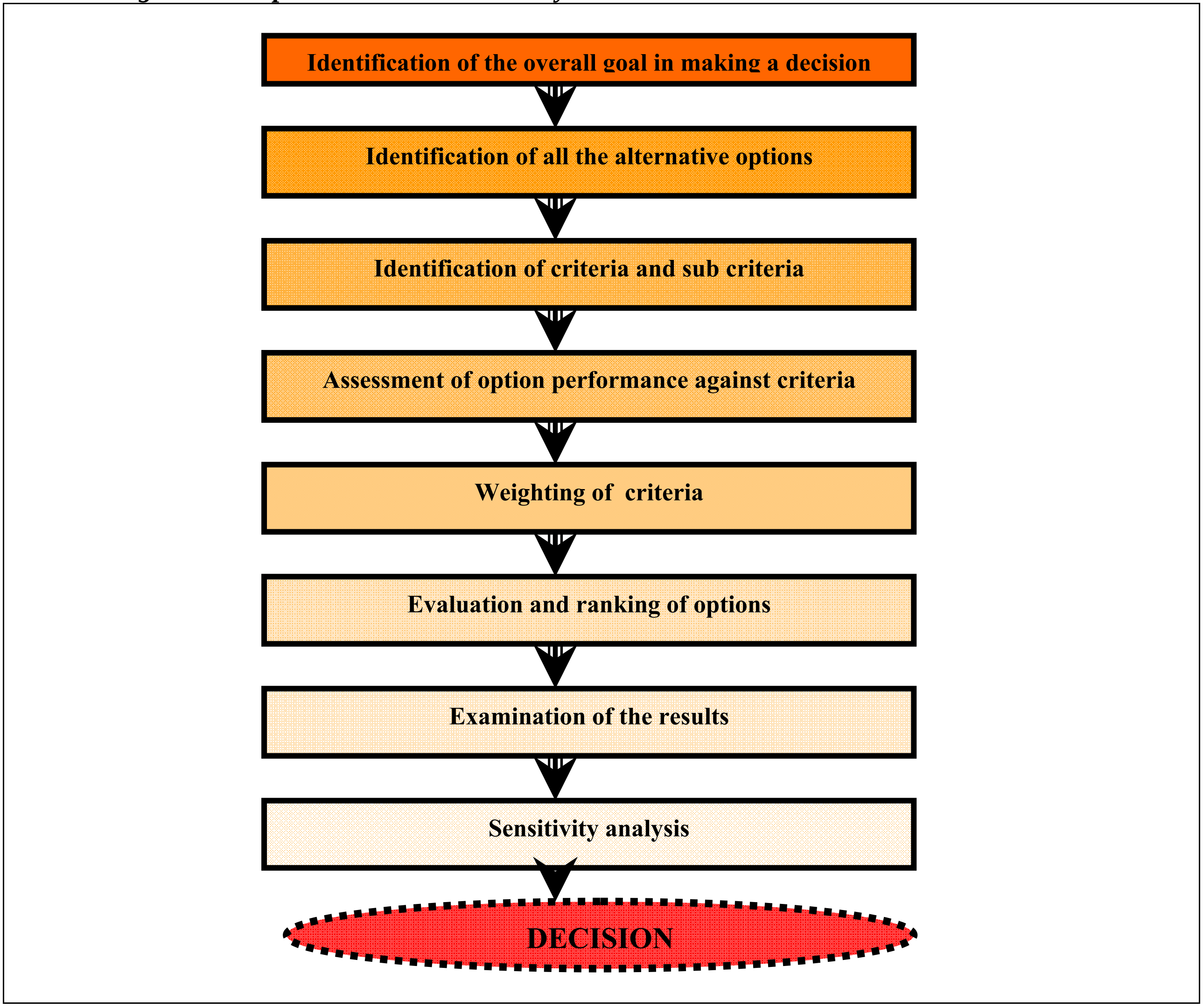
⇒ *Scores and weights, when used, are also explicit and are developed according to established techniques. They can also be cross-referenced to other sources of information on relative values, and amended if necessary;*
⇒ *Performance measurement can be sub contracted to experts, so need not necessarily be left in the hands of the decision making body itself;*
⇒ *It can provide an important means of communication, within the decision making body and sometimes, later, between that body and the wider community;*
⇒ *If scores and weights are used, it provides an audit trail.*

As seen, options are generated through involvement of all stakeholders which increases the likelihood of novel options being generated. In addition it provides a basis for involving stakeholders in the decision making process, therefore proposed solutions have a better chance at satisfying all stakeholders' objectives.

III. 4. The Stages of Multi Criteria Analysis

A multi-criteria framework helps tackle complex problems by breaking them down into smaller and more manageable components. Figure 3.1 shows the steps of the multi-criteria analysis.

Figure 3.1 Steps in Multi-Criteria Analysis[3]



As seen, MCA is a multi-step analysis method. Some steps require in depth analysis compared with the others and sometimes it is necessary to go back to previous steps and revise them. Additionally, it

[3] Adapted from the DETR multi-criteria analysis manual

is important to point out that in the management of contaminated lands, after the strategic decisions have been made, the decision makers will encounter other subsequent decisions to be made, such as the technology choice (this might happen after several years). Therefore the same steps must be performed so that the stakeholders make structured and efficient decisions at every level of the decision process (strategic, technical etc.) for contaminated land management.

The next part of the report will briefly present the steps of the MCA.

III.4.1 Identifying Objectives

The list of decision objectives should be comprehensive, consistent and without overlap. In case the list of objectives is developed by dividing an overall goal into subsidiary objectives this is called a "top-down" approach. Alternatively, the "bottom-down" approach is to identify all relevant objectives one by one and get them together. The objectives list will reflect the concerns and preferences of the decision maker and other stakeholders involved in the decision-making process. It is important to emphasise that there can be no prescriptive and generic listing of objectives.

In addition to a list of objectives, it can be useful to list any external factors that limit the breadth of the study; these can be termed constraints. Stakeholders may contribute potential constraints. In general, the constraints could be social, political and technical. For example in environmental decisions regulatory limitations may provide to be relevant constraints.

III.4.2 Defining Options

The next step in the analysis is the identification of the set of options. These should be gathered together after the objectives and constraints have been set. The options must be set up in a way that no viable option is omitted. Nevertheless it is suggested that it is advantageous to start with a limited, but diverse set. This gives the benefit of analysing a large number of options which are related to each other as well as discarding poorly performing options. In addition, stakeholders should be involved in the process of the discussion, development and approval of the options. Options that do not meet key constraints or screening criteria may be, at this point, excluded from further consideration.

III.4.3 Identifying Criteria and Sub-criteria

The options are evaluated by using criteria and sub-criteria. These are the measures of performance and establishing a soundly based set of criteria is the fundamental to the framework of MCA process.

Criteria represent the stakeholders' point of views and the criteria should integrate all the points of view expressed by the stakeholders. The selected criteria can be of a diverse nature: they may be selected unilaterally or through a group discussion with the various stakeholders. Identifying criteria is an important step in that the ranking of the options may change depending on the criteria selected.

There two main approaches in determining the criteria:

a) Value Focus Thinking: Criteria are determined in a hierarchical structure, known as value tree, leading from primary goals to main objectives, which in turn are further broken down to specific criteria,

b) Alternative-focused thinking: Criteria are identified through a systematic elicitation process, and may subsequently be grouped in broader categories (Diakoulaki and Grafakos, 2004)**.**

It should be noted that, even if an option perform badly against some criteria, it still can be assessed as the best option if it performs better in the other areas.

III.4.4 Assessing the Option Performance against Criteria

<u>The Performance Matrix</u>

A standard feature of multi-criteria analysis is performance matrix, or consequence table, in which each row describes an option and each column describes the performance of the options against each criterion. The individual performance assessments are often numerical, but may also be expressed as "bullet point" scores[4]*.*

[4] DETR Multi-criteria analysis manual, John Dodgson, Michael Spackman, Professor Alan Pearman and Professor Larry Phillips

Even a simple matrix can be a very powerful tool in assessing the different options. One can get valuable information by evaluating the performance matrix such as where each option performs well and where its shortcomings lie. The analysis of the matrix will lead to a more solid understanding of the situation than before. Qualitative and quantitative measures can be used while constructing a performance matrix. Qualitative measures can be natural units or numerical scales.

Even if the matrix is confined to qualitative description, natural units and very simple scales (such as stars) it is advisable to try to use similar numbers of criteria within each major sector of the value tree.

It is also worth considering the use of supplementary presentations of the data, such as graphs to help encourage people to think about the data in different ways and avoid giving undue weight to some factors relative to others[4].

<u>Valuing the Performance without the Scoring and Weighting</u>

Even in a simple matrix, it is unlikely that one option will outperform the others against all the objectives identified by the decision maker. If it does, this is called the dominance principle. However, "*dominance is limited in the extent to which it can differentiate between options specifically because it makes no assumption at all about the relative importance of criteria, nor does not employ any supplementary information beyond that directly displayed in the performance matrix*[4]".

<u>Valuing the Performance with the Scoring and Weighting</u>

Making the trade-offs between the objectives or criteria explicit simplifies making a decision. The stakeholder has to know how much she is able to give up from one objective to achieve another. This can be assured by;

a) Setting up how desirable are the performances of the options with respect to the criteria,

b) Weighting these derived functions and aggregating them into an overall measure of performance.

These can be achieved by converting performance measures to "values". Values are the normalized scores say, between 0-100, where the best favoured one is 100 and the worst is 0. However it should be noted that the scale between the best and the worst one may not be linear.

III.4.5 Weighting of Criteria

In order to establish a composite measure of performance across all the objectives selected, which in turn provides a basis for identifying preferred options, the criteria must be weighted according to how important each is regarded in relation to the others.

Weights represent a particular value and preference set and they are open to changes in case the stakeholders change their views.

III.4.6 Ranking of Options, Examination of the Results and Sensitivity Analysis

It is often best to conduct the decision process in a facilitated decision conference to determine the weights with a group of decision makers. By this method, decision makers will be educated with related background information and evaluation of performance and associated uncertainties. The performance of each option should be presented appropriately to assist the statement of preferences. The decision conference should discuss and revise the analysis framework and the background information. The most important point in a decision conference is to give the opportunity to stakeholders to discuss preferences in an open environment, so that they can establish a consensus on the weighting factors to be used.

After the set of weights has been derived, the weighted, normalised data should be analysed to discover the factors that are the most important in determining the ranking. Then the stakeholders should discuss whether they are content with the results that have been reached. In many cases iteration will be necessary to refine the alternatives, carry out more precise modelling or debate further the weights which should be used.

In many decision rules it is assumed that complete information is available. However, in real world situations, this is not the case and analysis should be made to investigate whether the preliminary conclusions are robust or not. Sensitivity analysis aims to identify the effects of changes in the inputs and the stakeholders' preferences on the outputs, in other words, on the ranking of options. If the changes do not significantly affect the outputs, then the ranking is assumed as robust and satisfactory. If the result is unsatisfactory, the stakeholders should return to the problem formulation step.

IV. Review of Different Multi-criteria Methods

MCA methods are distinguished from each other principally in terms of how they process the basic information in the performance matrix. Different circumstances will be better suited to some MCA procedures than others[4]. This part of the report briefly explains and provides limited information about the different approaches of MCA methods. This is partly because a full review of the methods involved in MCA analysis is not the main the subject of the report and partly because the overall report only deals with some of the methods which are much more applicable in to the management of contaminated lands. Examples of the application of some MCA methods are provided in the next section.

IV. 1. Continuous MCA Models (Multiple Objective Decision Making)

In case decision makers encounter a complex situation where more than one decision objective is to be considered then Multiple Objective Decision Making (MODM) provides a meaningful approach. MODM deals with the problems where the decision variables are infinitely variable, subject to some constraints and where there are multiple decision objectives. These situations are in fact a problem of optimisation and linear or non linear programming methods can be used to solve these kinds of problems. A linear programming problem may be defined as the problem of maximizing or minimizing a linear function subject to linear constraints. The constraints may be equalities or inequalities.

MODM methods are not so applicable due to the fact that;

a) they are structured in sophisticated mathematical forms,
b) prior to their application, constraints and objectives need to be formulated as equations,
c) they require large amount of time to collect data.

In practice, there are a few applications of MODM methods and even the assistance of the computers may not alleviate the problems with the method in that the users have to understand the complicated theory that lies behind.

IV. 2. Non Compensatory Methods

In multi-criteria analysis, a wide variety of techniques are available and these can be split into compensatory and non-compensatory techniques. In compensatory techniques poor performance in a number of criteria can be compensated for by high performance in the other criteria and may not be reflected in the aggregated performance of an option. In non-compensatory techniques poor performance in a number of criteria cannot be compensated for by high performance in the other criteria and will be reflected in the aggregated performance of an option (Jeffreys et al; 2004).

Non compensatory methods are used when:

a. Each option is evaluated against a common set of criteria set out in a performance matrix;
b. The decision maker is not willing to allow compensation i.e. for strong performance on one criterion to compensate for weak performance on some other criterion[4].

IV.2.1 Dominance

An option is dominated in case there is another option that excels it in one or more criteria and equals it in the remainder. The dominance method is as follows;

1) The first two options are compared and if one is dominated by the other, then the other one is discarded.

2) The remainder option is compared with the third one, and the dominated one is discarded.

3) Then the fourth option is introduced and the same process is repeated.

4) In the end, only the non-dominated option is left.

However, in general, the non dominated option will be more than one. That is why the dominance method is mainly used for the initial filtering. Also, the dominance method should be used with care since some dominated options might overall be better than the non-dominated options.

IV.2.2 Conjunctive and Disjunctive Selection Procedures

With the conjunctive method the decision maker has to set up a cut-off level, the minimum attribute values for the options, so that he accepts this option. In case this cut off level is more than the minimum attribute value, this option will be rejected. The cut-off level plays a key role in eliminating the unacceptable options. However, if the cut-off level is too high, then any option can be acceptable, therefore the cut-off level must be increased in an interactive way so that the options can be narrowed down to a single one.

The disjunctive method as well works the same way. First the decision maker has to choose a cut-off level for the criteria, however, an option is chosen if it exceeds a minimum cut-off level. If all options are disqualified, the decision-maker can reduce the cut-offs of one or more criteria and resume the evaluation of options.

IV.2.3 Lexicographic Ordering

The lexicographic ordering method works as follows;

1. First, the criteria are ordered from the most important to the least important,
2. Second, the options that satisfy the first criterion are identified,
3. Then the remaining options are compared with respect to the second criterion,
4. If more than two options satisfy this second criterion, a third one is used and so on down the list until just one option is identified.

Therefore a unique solution is not guaranteed with this method, and the procedure does not allow any trade-offs among criteria.

Lexicographic ordering does not produce a classification of all the feasible options and not all the information for the full set of criteria is necessarily used. In the process of comparing alternatives for a particular criterion it is possible to take account of measurement errors associated with the estimates for the impacts. For example, a threshold value can be defined which must be exceeded before one alternative is rated more attractive than another. By altering the threshold values for each criterion one can judge if the same alternative consistently appears as the most attractive[5].

IV.2.4 Elimination by Aspects

The Elimination by Aspect (EBA) model is presented by Tversky and it is the best known model among the non compensatory methods. The idea behind the EBA is,

1) the decision maker has to choose a threshold,
2) then eliminates unacceptable options depending on that threshold and,
3) goes on until the remaining options do not share any common attributes.

As seen this method brings together the lexicographic ordering method and conjunctive/disjunctive procedures.

IV.3. Multi-Attribute Utility Theory Models (MAUT), Aggregate Value Function Approaches and Multi Criteria Decision Analysis (MCDA)

With utility models, one can transform a numerical description of an option's performance against a range of different criteria into a single number. These are in fact mathematical models which represent the utility functions of options. Multi attribute Utility Theory (MAUT) models are designed to obtain the utility of the options that have more than one property. Therefore in the literature it is suggested to evaluate them on more than one criterion.

[5] A Multi-Criteria Decision-Making Method for Solar Building Design, Inger Andresen Norwegian University of Science and Technology Faculty of Architecture, Planning and Fine Arts Department of Building Technology.

MAUT is used when risks or uncertainties have a significant role in the definition and assessment of options. The main focus of MAUT is to assess individual's values and subjective probabilities in the presence of uncertainty. It uses the utility models, and for characterising the utility functions linear and exponential functional forms are often used. Once the information is obtained from the assessments, the model ranks the options and hence clarifies a situation for the decision maker. Sensitivity analysis is often involved in the assessment and decision process.

According to Belton (2002) there are two major components of a value function:

1) Value Functions: The assessment of each of the options with respect to the criteria.
2) Weights: Scaling factors which represent the relative importance of each of the criteria.

Then this information is summarized in order to provide an evaluation for each option.

IV.3.1 Value Functions and Scoring

As stated, a value function is used to determine the value of an option with respect to a criterion. Using relative judgements, a value function can be constructed by transforming a natural scale into a value scale. An alternative is to construct the value scale by direct judgement in case there is no physical measurement.

IV.3.2 Weighting

Weights serve to express the importance of each criterion relative to others. The weights which are assigned to a criterion represent a scaling factor that relates scores for that criterion to the scores for all other criteria.

IV.3.3 SMART (Simple Multi-Attribute Rating Theory)

SMART is a simpler version of the Multi-Attribute Utility Theory (MAUT). While MAUT incorporates the concept of utility functions, SMART uses value functions. The difference between the value functions and the utility functions is that utility functions takes into account the attitude of risk. Therefore the value functions are less complicated than the utility functions.

IV.3.4 Multi-Criteria Decision Analysis (MCDA)

Multi-criteria decision analysis (MCDA) is a form of MCA and has been used widely in both public and private sector. However, in the literature MCDA and MCA is not differentiated and this is not correct. In fact, decision analysis is originated in 1966 with Ronald A Howard. [Decision Analysis: Applied Decision Theory in "Proceedings of the 4th International Conference on Operational Research" (Eds. D.B.Hertz and J. Melese) pp.59-71]. In the 1960's a new system was developed in structuring the choice between the decision options in the presence of uncertainty about the future events which affected their consequences. This was represented as a decision tree and the consequences were taken to be a one dimensional performance measure. This approach is known as decision analysis. This formulation was extended to allow for multiple criteria, and the approach developing from this innovation is known multi criteria decision analysis (Rosenhead and Mingers, 2005)

In DETR multi-criteria analysis manual MCDA is explained as "*MCDA is both an approach and a set of techniques, with the goal of providing an overall ordering of options, from the most preferred to the least preferred option. The options may differ in the extent to which they achieve several objectives and no one option will be obviously best in achieving all objectives. In addition some conflict or trade-off is usually evident amongst the objectives; options that are more beneficial are also usually more costly, for example.*

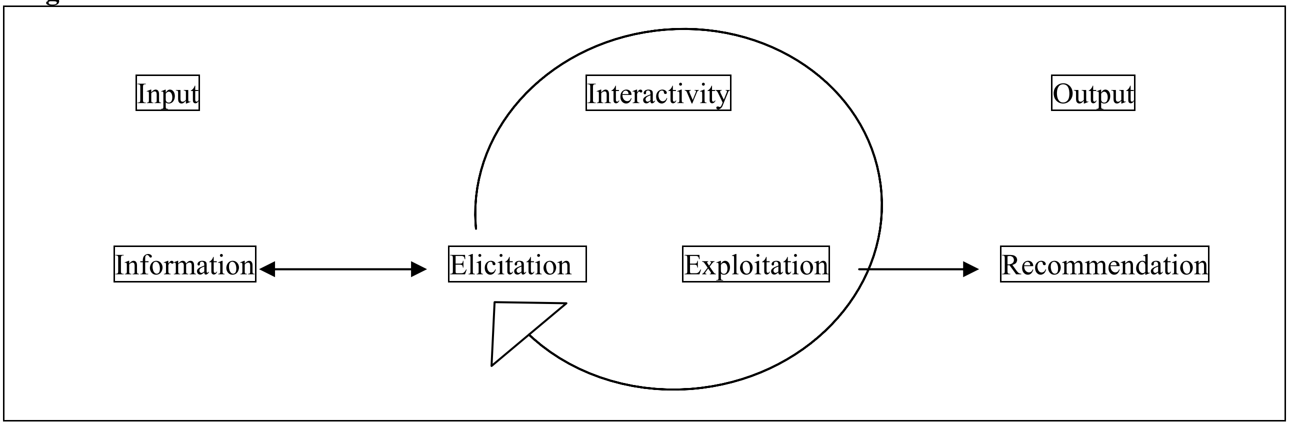
MCDA is a way of looking at complex problems that are characterised by any mixture of monetary and non-monetary objectives, of breaking the problem into more manageable pieces to allow data and judgements to be brought to bear on the pieces, and then of reassembling the pieces to present a coherent overall picture to decision makers. The purpose is to serve as an aid to thinking and decision making, but not to take the decision. As a set of techniques, MCDA provides different ways of *disaggregating a complex problem, of measuring the extent to which options achieve objectives, of weighting the objectives, and of reassembling the pieces".*

In summary, MCDA's general objective is to assist decision makers to assess decision problems where more than one point of view has to be considered, and it does so by not forcing any stakeholder to make decision at any cost.

MCDA process requires a strong interaction between the stakeholders and the analyst. The discussion step is very important for a proper interpretation of the stakeholders' preferences.

The figure below shows the MCDA process[6]

Figure 4.1 General Scheme of a MCDA Process



As seen from the figure MCDA is an interactive process where the stakeholders' preferences and the interaction play active role in the idea development and evolution. Therefore MCDA increases the self learning process. This interactive structure of the MCDA stops when the decision maker is fully content with the output. Also such interactivity allows the stakeholders easily to modify their initial thoughts which in turn help the stakeholders reach a consensus. However, the interactivity should be performed in a way which avoids too much technicality. Qualitative questioning is preferable to quantitative.

Literature highlights a number of advantages of MCDA:

First, stakeholders are directly involved in the decision making process in terms of detecting their preferences and values concerning the decision criteria. As a result of this, the elicitated values of the stakeholders better reflect their concerns and priorities.

The second advantage of MCDA is that it gives the stakeholders an incentive to contemplate conflicts between points of view. Therefore MCDA is a kind of interactive learning process. This model enables the decision makers to understand clearly the sub components of the problem at hand. As a result, it stimulates constructive debates and stakeholders reach to a commonly negotiated solution.

Thirdly, MCDA opens the way for stakeholders to understand the different backgrounds of the other participants, capture their ideas and understand their point of views. That is why MCDA can be seen as a multi-disciplinary approach.

Fourthly, MCDA approaches can take into account a wide range of criteria which can be quantitative as well as qualitative. Therefore, MCDA enables decision makers to perform much more comprehensive analyses.

Finally, MCDA is objective and less prone to biases. Preferences of stakeholders can be expressed freely and facilitated.

IV. 4. The Analytical Hierarchy Process

Analytical Hierarchy Process (AHP) was developed by Saaty (Saaty, 1990). AHP is mainly concerned with,

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[6] Progressive Methods in Multiple Criteria Decision Analysis, Patrick Meyer, Luxembourg University, PhD thesis, 2007.

a. The formulation of the problem in the form of a hierarchy,
b. The judgment of pairwise comparisons.

"The hierarchy has at least three levels:

- *Top level: Overall goal of the problem.*
- *Middle level: Multiple criteria that define options.*
- *Bottom level: Competing alternatives.*

When criteria are highly abstract, such as "well being", sub-criteria are generated sequentially through a multilevel hierarchy[5]."

Saaty generated a nine point scale in order to assist a decision maker to evaluate the pairwise comparisons. The table below shows this nine point scale. The numbers express degrees of preference between the two elements.

Table 4.1 The fundamental scale for pairwise comparisons[4].

How Important is A relative to B?	*Preference Index Assigned*
Equally Important	*1*
Moderately Important	*3*
Strongly more Important	*5*
Very strongly more important	*7*
Overwhelmingly more important	*9*

IV.4.1 The AHP Procedure

Once the criteria B_i, B_j, have been set up, the next step is to form a pairwise comparison matrix where the number in the i^{th} row and j^{th} column gives the relative importance of B_i as compared to B_j. Then the next step is normalizing the weights by computing the sum of each column of the matrix and dividing each column by the corresponding sum. Also at this stage the consistencies of decision makers' preferences are tested. The next step is to use the weights to obtain scores for the options and make a decision.

IV.5. Outranking Methods

The outranking methods are different from the aggregate value functions because they do not accept that all the options are comparable. Outranking methods assume that a decision maker or a group will be unwilling or unable to compare some options in some circumstances. With outranking methods, the output will not be a value for each option, but an outranking graph indicating preferences.

These methods concentrate on the fact that in MCA methods one tries to form a preference ordering of options. As each criterion generally leads to different ranking of the options, assuring a consensus on the ranking is a problem. Outranking methods perform pairwise comparisons of options to determine the preferability of each option over the other ones. Then, by aggregating the relative choices a consensus can be reached. Finally, the consensus over the preferences leads to the final dominance.

ELECTRE I, II and III are the best known outranking methods. The ELECTRE I method is used to construct a partial ranking and choose a set of promising options. ELECTRE II is used for ranking the options. In ELECTRE III an outranking degree is established, representing an outranking creditability between two options which makes this method more sophisticated.

IV.6. Fuzzy MCA

The value of a potential solution may be determined by criteria that may be qualitative as well as quantitative. Sometimes the evaluation of quantitative criteria may be based on probabilistic calculations. On the other hand the qualitative criteria cannot be evaluated by this method. The main problem here is the nature of the information that is represented by the qualitative attributes.

Linguistic specifications such as “beautiful”, “better” have no quantitative variable on them. If an option cannot be described precisely and is characterized by subjectivity, it is called fuzzy. Fuzzy mathematics is used to model this fuzzyness.

Fuzzy mathematics has been incorporated in MCA. The main contribution of the fuzzy mathematics is to stress that judgments are ambiguous and to try to incorporate this ambiguity in the analysis.

IV.7. Even Swaps

The aim of the even swaps process is to carry out even swaps that either make options irrelevant (i.e. all the options have equal consequences on this criteria), or options dominated (i.e. some other option is at least as good as this option on every criteria). These can be eliminated, and the process continues until only the most preferred options remains. There is also the concept of practical dominance. Option **x** practically dominates option **y** if **y** is slightly better than **x** in only one or few options but **x** clearly outranks **y** in several other criteria. Thus, **y** can be eliminated in order to reduce the problem in obvious cases without the need to carry out unnecessary even swaps tasks (Mustajoki and Hämäläinen, 2006).

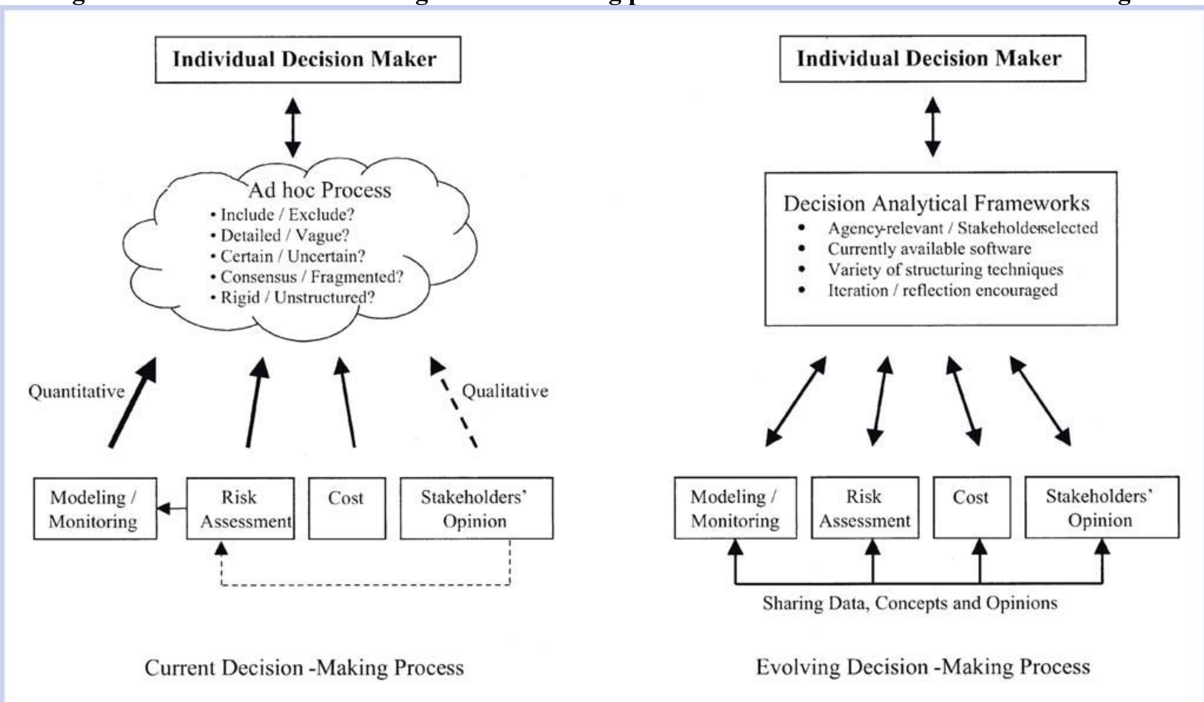
V. Application of MCA Methods in the Management of Contaminated Land

V.1. Introduction

There generally exist 4 types of technical input received by decision maker in environmental management projects which are the results of modelling and monitoring studies (including socio-economic impacts), risk assessment, cost or cost-benefit analysis, and stakeholder preferences. Decision makers face several problems in environmental management projects. The first problem is the limited availability of guidance on the ways of judging the relative importance of information from each source. Secondly, decision makers receive information in different forms. For instance, socio-economic analyses contain more qualitative judgment whereas the results of modelling and monitoring studies incorporate quantitative information. Thirdly, decision makers mostly do not receive structured information about stakeholder preferences. Even if they receive this information, the way of dealing with it can be subjective and decision process will not always be reliable and fair. Therefore, decision makers are not provided with necessary information to enable their choice between identified project options. Figure 5.1a visualises the current decision making process. (Kiker et al., 2005)

There are new concepts in terms of decision making for the management of contaminated land. In Gregory A. Kiker et al paper, the new concepts are reflected in Figure 5.1b. As already stated, MCA can be applied to assess value judgements of both individual and group decision makers. The advantage of MCA approaches in multiple stakeholder decisions is to make the decision makers see the range of point of views which in turn helps the decision makers understand the others' values and opinions. The evolving decision making process shown in Figure 5.1b is applicable to decision making in environmental projects as well as contaminated sites.

Figure 5. 1. Current and evolving decision-making processes for contaminated sediment management[1]



In addition, using MCA approaches in environmental decisions provide other benefits for the involved stakeholders:

- They facilitate the analysis by synthesing large amounts of information,
- Motivate people to ponder the objectives and priorities,
- Give a support to the analysis of conflicts among objectives,
- Increase the transparency of the decision,

- Get together different types of information,
- Address factual information (Felix and Nijboer[7]).

For the sated reasons, using MCA techniques in making a decision about what to do with contaminated land provides lots of benefits to decision makers.

V.2. Reference Land Management Cases

The contaminated land situations likely to be considered are wide and varied, however it is necessary to consider a number of hypothetical "reference" cases that can be used to evaluate the potential of the options comparison methods described in Section IV. Therefore, three cases have been defined, based on the experience of experts in radioactively contaminated land.

The reference cases have been defined in order to capture the main "degrees of freedom" experienced in contaminated land situations, namely:

- ▲ the **characteristics of the contamination** (area, location, levels of contamination);
- ▲ the **stage of planning** – from strategic to implementation; and
- ▲ the **range of stakeholders** with an interest in the issue.

The cases are intended to cover opposing ends of these aspects:

- ▲ small areas of limited contamination to large sites with some substantial contamination;
- ▲ initial strategic development to specific technology assessment for implementation of the management strategy; and
- ▲ options comparison to inform management and perhaps regulators to full engagement of local communities and perhaps national stakeholders.

It is notable that these separate aspects are in some cases correlated, for example "small" problems and "technology implementation" considerations are less likely to have the interest of a wide range of stakeholders. Consequently, the following combinations can be identified:

Case 1: A **small patch** of contaminated land on a controlled nuclear or defence site, considering options for **implementation**, with interest of **few stakeholders** (management and regulators, primarily).

Case 2: A **large area** of contaminated land (perhaps within a site) for which an implementation technology needs to be identified, with the **local stakeholder** interest (management, regulators and some in the local community).

Case 3: A whole **site**, considering **strategic** options, with interest of **many stakeholders** (management, regulators, local and some national stakeholders).

Further description of these cases follows.

Case 1 (Simple)

This case considers a nuclear or defence site with a small isolated patch of contamination (perhaps a few m^2) on a site that is already managed. Consideration needs to be given to what to do. An overarching strategy already exists for the site, which will influence how the land is dealt with. This, and the fact that the land is small and not very significant in hazard, means that extensive analysis is unwarranted, and only a few, specific, options need to be considered. For example, the options could comprise:

- ▲ excavate and dispose of as waste;

[7] Decision making in environmental management; Francisca Felix and Matthijs Nijboer, http://www.p2pays.org/ref/26/25564.pdf Publication date is not specified.

- ▲ immobilise with grout;
- ▲ keep under control by erecting barriers; etc.

The factors considered include: worker safety, discharges, consistency with the site end state objective and cost.

Case 2 (Intermediate)

This case considers a nuclear or defence site with a well characterised extended area of contamination on a site that is already managed, perhaps a patch of land of tens of square metres contaminated to a depth of a few metres. In places the contamination is at significant levels that cause regulatory concern. An overarching strategy already exists for the site, which will influence how the land is dealt with. However, it will be potentially costly and the regulator demands a thorough analysis of the available technologies. Some specific options are therefore considered, such as:

- ▲ excavate the most heavily contaminated area and dispose of as waste;
- ▲ include permeable reactive barriers around the heavily contaminated area;
- ▲ apply groundwater treatment and immobilise residual contamination with cement grout; etc.

These more specific options need to be evaluated by a broader range of criteria, perhaps about 20. For example, "safety" is broken down into a range of criteria such as: radiological safety during implementation, non-radiological hazards during implementation, risk of accidents, long-term public safety from residual contamination, transport safety. The emphasis on the criteria is on those associated with safety and environmental performance, technical performance and cost.

Case 3 (Complex)

This case is concerned with the development of an overarching strategy for managing contamination across a whole site. The site has various areas of contamination, some small and of limited significance, some substantial. The contamination is under a safe management regime, but the site is being decommissioned and the intention is to prepare it for eventual re-use by non-nuclear industries. Specific management options for the particular areas of contamination are not required at the present time, but some important strategic decisions need to be made, such as:

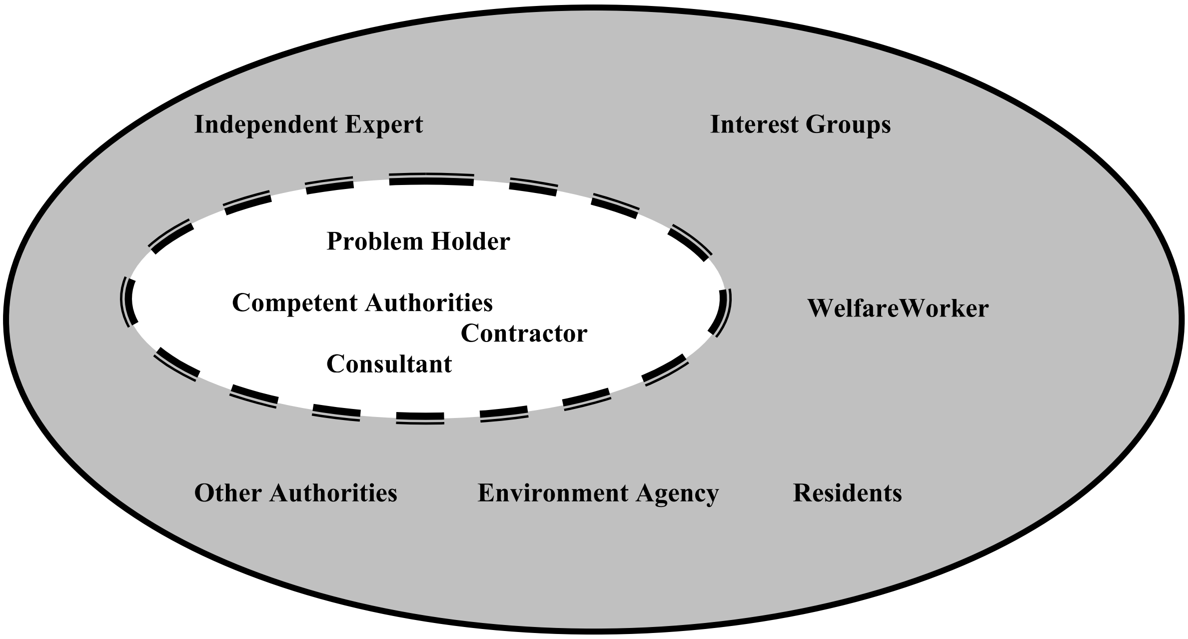
- ▲ remediate the whole site by excavating all contamination and disposing of it elsewhere;
- ▲ keep control of the site for an extended period to allow radioactive decay and monitored natural attenuation to reduce concentrations to level at which the site could be released;
- ▲ place impermeable barriers over the contamination and make a case that this ensures sufficient safety to permit the site to be released; etc.

In this evaluation there is a significant degree of public interest. The assessment of the strategy options therefore needs to cover a range of criteria relevant to the whole range of stakeholders. This requires a reasonably detailed list of criteria, which, as well as health, environmental, technical and cost issues, covers social factors such as: nuisance, blight, employment prospects and burdens on future generations.

V.3. Parties Involved in Contaminated Land Management Decisions

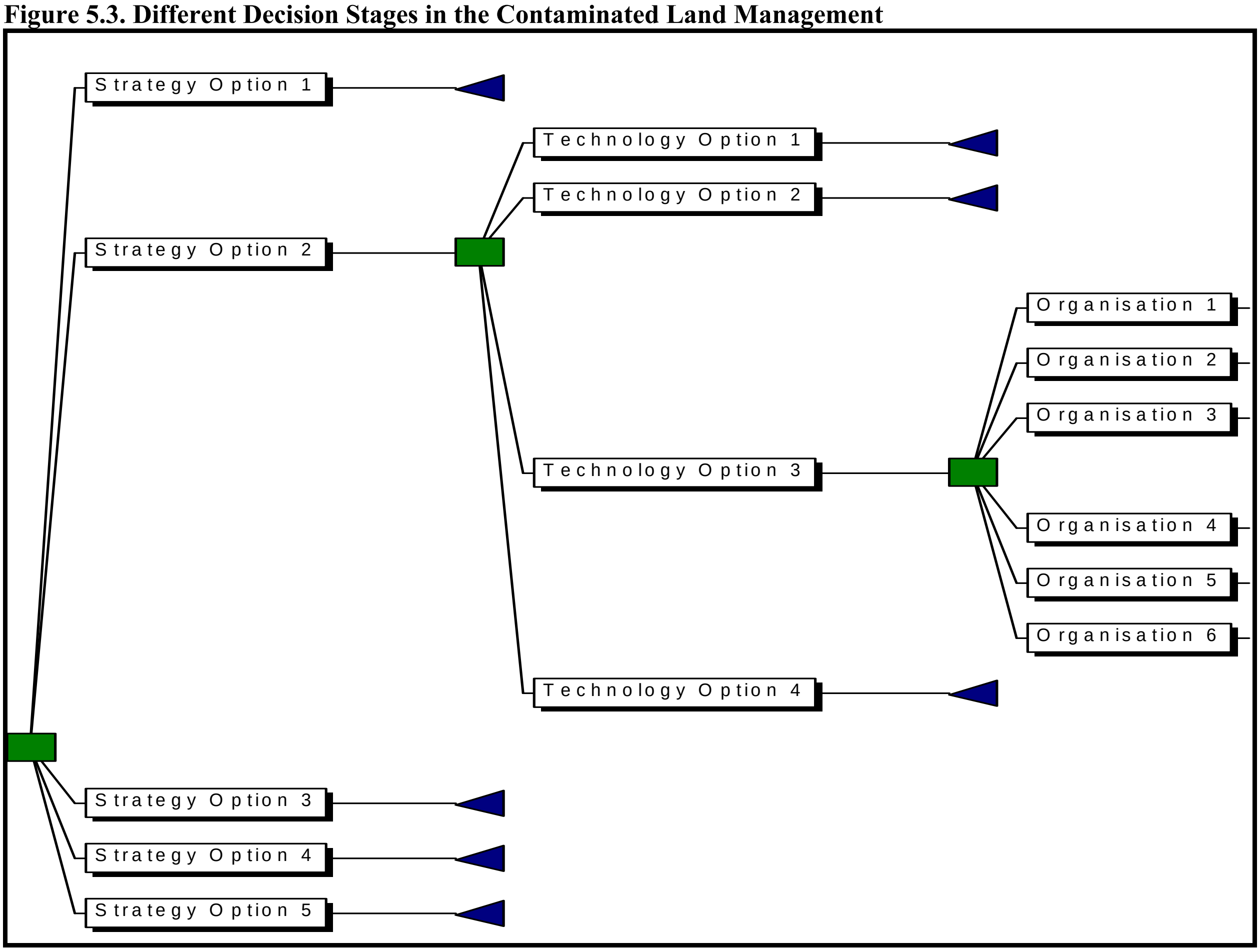
Cleaning up operations involve a number of stakeholders which can affect the decision. The figure below shows the main actors in a decommissioning project. According to Felix and Nijboer the parties in the centre of the figure have the strongest influence on the choice.

Figure 5.2: Network of Actors involved in the selection of a remedial alternative[7]



These actors might not participate in all of the decision processes. As already discussed on the Section III.4, the decision makers have to make new decisions after the strategic decisions such as technology choices. The figure below is prepared to give an idea about the decision processes in the UK.

Figure 5.3. Different Decision Stages in the Contaminated Land Management



As seen from the figure, first of all, the decision makers encounter the strategy choice. At that stage they have to decide the basic principles for what to do with the contaminated land. Supposing they decided second strategy which is, say, the minimum practicable restoration they now have to make decisions concerning the technology choices- how to achieve the minimum practicable restoration with available technologies? Finally, it will be necessary to choose an organisation to actually do the work. The decision which will be made at this stage is about the capabilities of the organisations, their proposed methods and their price offers. The first phase of these kinds of decisions incorporates strategic choices whereas the latter ones are much more technical. Therefore the actors will be different depending on where they will be on the decision cycle. For example the local community engagements would generally decrease as the decisions become more technical. These concerns have been taken into account when proposing solutions about which method should be used in these stages.

V.4. Different Interests in Contaminated Land Management Decisions

The stakeholders' interests sometimes are the same, but sometimes the interests can differ. The table below shows examples of the different interests of various actors in contaminated land management.

Table 5.1. Indication of the Different Interests of Various Actors[7]

Players	Interests
Problem Holder	Cost effectiveness
	Functionality of soil
	Efficient decision making
Authorities	Multifunctionality of soil
	Maximisation environmental balance
	Consistent policy
	Efficient decision making
Consultants	Looking after the interests of the client (problem holder of competent authority
	Efficient decision making
Third parties, residents	Risk reduction
	Minimal limitations of use
	Minimal nuisance
	Efficient decision making
Contractor	Looking after the interest of the client
	Efficient decision making

As seen from the table, sometimes stakeholders' interests coincide, however they have different priorities. Therefore, in the management of contaminated land, if the decision making process is transparent and efficient then all the parties' views will be equally reflected into the decisions. This will definitely increase the trust among the decision makers and the process is more likely to result in a consensus.

V.5. Application of MCA Methods for Options Comparison

V.5.1 Determining the Criteria

As stated in Chapter 2, in general there are a limited range of broad options about what to do with contaminated land. Examples of typical criteria that are considered are as follows:

Table 5.2. Criteria Used to assess the Chapelcross End State Options

Criterion Group	Criteria
Human Health and safety	Public radiation dose from soil and groundwater (Post-End point)
	Public risk from natural or human disruption (Post-End point)
	Public risk from site and discharges (Pre-End point)
	Risks from transport
	Occupational radiation exposures (Pre-End point)
	Risks from other industrial hazards
Impacts on natural, physical and built environments	Radioactive contamination of the land and sea
	Non-radioactive contamination of the land and sea
	Environmental quality
	Natural resource use
Amenity and quality of life	Visual impact
	Noise
	Transport
Security	Potential for misappropriation of radioactive material
	Vulnerability
Technical performance and practibility	Project risk
	Requirements for technical development
	Timescale to implementation
	Flexibility
	Radioactive waste generated
	Decommissioning strategy impact
Social and economic impacts	Flexibility of site use post-end point
	Potential for job creation (Post-end point)
	Burden on future generations
	Person-hours of effort to achieve End State
Costs	Pre-End Point costs
	Post-End Point costs

For this example, relating to the assessment of strategic options for the clean-up of a nuclear site during decommissioning, there are 7 criteria groups and 27 criteria to assess the options. As stated these criteria and sub criteria may not be the same when the stakeholders make a technical decision.

V.5.2 Evaluation of the Applicability MCA Methods in the Management of Contaminated Land

As discussed in Chapter IV, MCA methods incorporate a wide range of different approaches. Some of them are quite complicated and do not present much help for practical decision making. Existing literature offers little help in terms of using MCA techniques to facilitate decision making for the management of contaminated land. However, it is clear that the ease of use can be the main criterion for choosing which method would be the most efficient in the evaluation of MCA methods in the contaminated land management for all cases.

In simple cases, identifying the criteria may alone provide enough information for stakeholders. With other words, constructing the performance matrix may be the final analysis for making a decision. In complicated cases, using the MCDA may be the best method. The main criteria in using a specific method for the contaminated land management are whether the method which is used is;

a. simple,
b. transparent,
c. implemented without difficulties and
d. open to a wider range of users.

Putting all of these criteria together, some methods which is presented in Chapter IV are not very useful in option comparison for the management of contaminated land. The next section briefly explains why some of the methods do not provide meaningful approaches on that issue.

A) Methods which will not be used in the Management of Contaminated Land

This section of the report briefly presents some of the MCA techniques which are not used to compare the different options in the contaminated land management. Therefore, examples concerning their applications have not been provided within the report, however Appendix A provides with some short explanations depending on their applications.

1. Multi-attribute Utility Theory (MAUT)

Even though it provides strong theoretical insights, it is not very useful to help stakeholders to undertake complex multi-criteria tasks. MAUT requires estimation of the parameters in a mathematical form. It requires developing a utility function and making trade-offs which is both theoretical and time consuming. Therefore it will be relatively complex for some stakeholders to understand its structure and comment on its findings. Also it must be implemented by the experts. But if the stakeholders are a group of experts then it can be used effectively in that it has a sound theoretical base.

2. ELECTRE

As stated in Chapter IV, ELECTRE is the best known outranking method. However, the ELECTRE method is very complicated. The first step in this method is to form discordance and concordance matrices. In case there are lots of options and criteria, this method is not easy to implement and requires repetitive numerical calculations. Therefore, it is not open to a wide range of users.

3. Fuzzy Methods

In the literature there are some concerns about the implementation of these methods. In DETR it is stated as follows;

"a lack of convincing arguments that the imprecision captured through fuzzy sets and the mathematical operations that can be carried out on them actually match the real fuzziness of perceptions that humans typically exhibit in relation to the components of decision problems,

- doubts as to whether ***prescriptively*** *trying to model imprecision, which is in some sense a* ***descriptive*** *reflection of the failings of unaided human decision processing, is the right way to provide support to deliver better decisions;*

- failure to establish ways of calibrating membership functions and manipulating fuzzy values that have a transparent rationale from the point of view of non-specialists".

Therefore, these methods are not easy to implement and do not have clear theoretical foundations for modelling decision makers' preferences.

4. Linear Programming (Multi Objective Decision Making)

As mentioned in Chapter IV, MODM methods did not found a lot of applications in practice. This is because their structures are mathematical forms, objectives and constraints need to be formulated as equations and they require large amount of time to collect the data.

B) Methods which will be used in the Management of Contaminated Land

This section of the report explains the methods which provide meaningful approaches in terms of option comparison for contaminated land management. They are much easier to implement, provide much more transparency and are open to a wide of users than the other methods. They are implemented easily because they incorporate simple methods, so every stakeholder can easily participate in the decision process. Hypothetical examples illustrate their application.

1. Direct Evaluation of Performance Matrix

In the simplest form of MCA, a performance matrix may be the final analysis. The stakeholders assess the extent to which their objectives are met by the entries of the matrix. This method is suggested when there is a time limit in making a decision. However, it may also lead to the use of unjustified assumptions which will cause incorrect ranking of options. The table below is prepared to show how the performance matrix can be implemented. Options and criteria are taken from the work prepared by the Quintessa Ltd.

Table 5.3 Performance Matrix Based on Consequences

CRITERIA GROUPS	OPTIONS				
	Do Nothing	Remove some or all of the contamination, and then dispose of it in purpose-built facilities for radioactive waste	Immobilise some or all the contamination in the ground	Further isolate the contamination by the addition of barriers	Adopt a mixture of the above options
Human Health and safety					
Impacts on natural, physical and built environments					
Amenity and quality of life					
Security					
Technical performance and practibility					
Social and economic impacts					
Costs					

WORDS DESCRIBING CONSEQUENCES

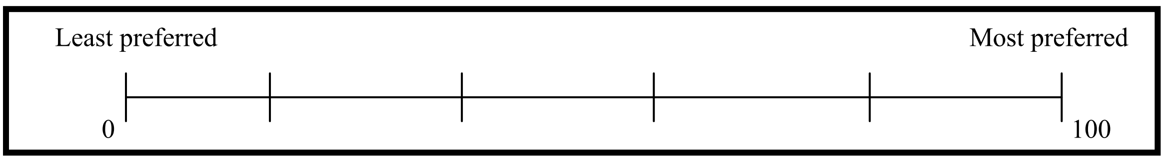
Every cell within the matrix will be the words describing the consequences of the options against criteria groups. With the direct analysis of the performance matrix, some preliminary information about options' relative consequences can be obtained. This method is the easiest one in that it only requires a simple qualitative description for each option against each criterion. Therefore for simpler cases, it is often sufficient enough to perform a solid analysis.

2. Dominance and Linear Additive Methods

In case the performance matrix is constructed and the stakeholders cannot make a decision depending on the direct evaluation of it, then the second step in the analysis is to score the cells so that the decision makers can check whether there exists dominance among the options.

To perform a dominance analysis, a two step procedure should be done: First scoring all the cells and then weighting the criteria according their relative importance. If the stakeholders face a simple case then the dominance analysis provides very useful tools in comparing the options. All we have to do is simply look for dominance among the options' scores against each criterion and in case there is a non dominated one, then it will be the best option.

To score the cells, first of all the stakeholders must agree upon the most and the least preferred options on each criterion. After determining the most and the least preferred one, scores have to be assigned to the remaining options on each criterion, bearing in mind that the most and the least scored one. With other words, more preferred options for each criterion score higher on the scale and less preferred score lower. The figure below shows the relative strength of preference[4].



Once the numbers are assigned to cells, the dominance analysis can be performed. Looking at our performance matrix in Table 5.4, (The options performances against the criteria are hypothetical.) we can see that the option B dominates option A. Therefore option A must be eliminated from the table. However, as seen from the example, there is no absolute option that dominates all the others.

Table 5.4 Performance Matrix with Scores

CRITERIA GROUPS	OPTIONS				
	Do Nothing (A)	Remove some or all of the contamination, and then dispose of it in purpose-built facilities for radioactive waste (B)	Immobilise some or all the contamination in the ground (C)	Further isolate the contamination by the addition of barriers (D)	Adopt a mixture of the above options (E)
Human Health and safety	30	44	**MOST PREFERRED MERITS (=100)**	35	**LEAST PREFERRED MERITS (=0)**
Impacts on natural, physical and built environments	**LEAST PREFERRED MERITS (=0)**	**MOST PREFERRED MERITS (=100)**	90	99	50
Amenity and quality of life	45	56	55	**LEAST PREFERRED MERITS (=0)**	**MOST PREFERRED MERITS (=100)**
Security	**LEAST PREFERRED MERITS (=0)**	45	40	**MOST PREFERRED MERITS (=100)**	56
Technical performance and practibility	67	**MOST PREFERRED MERITS (=100)**	60	69	**LEAST PREFERRED MERITS (=0)**
Social and economic impacts	45	66	**LEAST PREFERRED MERITS (=0)**	**MOST PREFERRED MERITS (=100)**	45
Costs	90	**MOST PREFERRED MERITS (=100)**	56	83	**LEAST PREFERRED MERITS (=0)**
Total (∑)	277	**511**	401	486	251

In case one dominates all the others then this option clearly the best one. However in case there is no option that dominates the others then aggregation method can be used to evaluate the options' performance. This method as well is simple to implement. For the complicated cases it can be used with ease. As seen from the table, option B's score is the biggest one, so clearly this option is to be chosen. Note that at that stage criteria are not weighted. In fact the stakeholders can simply weight the criteria regarding the relative importance of each criterion and then multiply these weights of the criteria by the scores of the options against each criterion and reach a total score on each of the options.

This method is very useful in that it has straightforward intuitive appeal. When all the stakeholders involved in the process, it will ensure the transparency and increase the trust among the different stakeholders. Therefore, it provides with a robust and effective support to decision makers.

However, as with many tools, it can be misused. Its very ease of use can encourage this. In particular, this is critical with regard to the scaling of options' performances on criteria, the weighting of criteria, and the relationship between weight determination and the scales on which performance on each criterion is measured. Failure to follow the proper logic of the model can lead to an MCDA that appears clear and well-founded, but which is, in fact, misleading and not a true reflection of the decision making group's understanding of the problem[4]"

In short, linear additive methods can be easily implemented in simple, intermediate as well as complicated cases. As seen from the example, the steps of this method are very transparent, clear and open to discussion. Therefore, the stakeholders will easily understand the method and they will be eager to participate in the decision process which in turn increases the trust among them.

3. Multiple Criteria Decision Analysis

MCDA is in fact a kind of linear additive model. However, this time the weighting will be used to reflect the relative importance of criteria. With other words, the steps used here are the same except the weighting method. MCDA uses "swing weighting".

Swing weighting is used to understand the criteria weights and the procedure is as follows:

1. The stakeholders consider the swing from worst to best for each option,
2. line them up in order of value increments,
3. Determine the multiples of the increments.

In a swing weighting procedure, the stakeholders rank the criteria by asking the question "If I were faced with an option that had the worst values of all of the criteria, and I could swing one criteria from worst to best, which would I swing?" This is the most important criteria, and they do this repeatedly to determine the second-most important, third-most important, etc.

In our example, suppose that the swing on the human health and safety is the most important (λ_1). The swing on the second option is roughly the same (λ_2) compared to first one. However the swing in the amenity and quality of life (λ_3) is about one and a half as small as the second one. Again let's suppose the swing on the third one and the fourth one (λ_4) is the same. The swing on the last three one are the least important (λ_5, λ_6, λ_7), say about twice as small as the first one.

From these preferences, the equation set is as follows:

$$\lambda_1 = \lambda_2$$

$$\lambda_1 = 1.5\lambda_3$$

$$\lambda_3 = \lambda_4 \qquad \text{where} \quad \lambda_1 + \lambda_2 + \lambda_3 + \lambda_4 + \lambda_5 + \lambda_6 + \lambda_7 = 1$$

$$\lambda_5 = \lambda_6 = \lambda_7$$

$$2\lambda_5 = \lambda_1$$

From these set of equations the solution set;

$$\lambda_3 = \lambda_4 = 0.14;$$

$$\lambda_1 = \lambda_2 = 0.21;$$

$$\lambda_5 = \lambda_6 = \lambda_7 = 0.10$$

Now that the weights are determined using the swing weighting method we can easily evaluate the relative scores of the options by performing simple multiplications. The table below shows each of the options' total scores after multiplying the options' performances against criteria with the relative weights.

Table 5.5 Multi Criteria Decision Analysis Example

CRITERIA GROUPS	Weights	OPTIONS				
		Do Nothing	Remove some or all of the contamination, and then dispose of it in purpose-built facilities for radioactive waste	Immobilise some or all the contamination in the ground	Further isolate the contamination by the addition of barriers	Adopt a mixture of the above options
Human Health and safety	**0.21**	30	44	100	35	0
Impacts on natural, physical and built environments	**0.21**	0	100	90	99	50
Amenity and quality of life	**0.14**	45	56	55	0	100
Security	**0.14**	0	45	40	100	56
Technical performance and practibility	**0.10**	67	100	60	69	0
Social and economic impacts	**0.10**	45	66	0	100	45
Costs	**0.10**	90	100	56	83	0
Total (∑)	**1.00**	32.8	**70.98**	64.80	67.34	36.84

The strength of MCDA is that it can bring together many different concerns and it recognises that the decisions are not made on the assessment of one single criterion. Second, the decision makers jointly define the weights of the criteria which in turn increase the understanding of each stakeholder's point of views. This method is an interactive one and it increases the degree of the consensus. In addition subjective judgments are combined with objective assessments. For these reasons it can be easily implemented with the complicated cases.

4. Even Swaps

First, shareholders look for the dominance. If any option does not dominate all the others, one method is to see if the group can discuss to consensus. If the group does not reach a unique solution, then even swaps method can be useful.

This time let's make some small changes in performance matrix without changing the criteria. (Only some scores are changed) To perform an even swap analysis, first let's compare column B with column A. As seen, B dominates A and C. So C and A is eliminated from the performance matrix. Then let's compare the column D with E. Here D practically dominates E because it performs better on nearly every criteria. So E is eliminated from the matrix. Now we have to compare B and D. As seen from the table below, we can eliminate technical performance and practibility in that they are the same at both B and D.

Table 5.6 Application of Even Swaps Method

CRITERIA GROUPS	OPTIONS				
	Do Nothing (A)	Remove some or all of the contamination, and then dispose of it in purpose-built facilities for radioactive waste (B)	Immobilise some or all the contamination in the ground (C)	Further isolate the contamination by the addition of barriers (D)	Adopt a mixture of the above options (E)
Human Health and safety	30	44	42	35	19
Impacts on natural, physical and built environments	32	100	90	99	50
Amenity and quality of life	45	56	55	34	76
Security	21	45	40	67	56
Technical performance and practibility	67	70	60	70	56
Social and economic impacts	45	66+**21**	0	87	45
Costs	90	91	56	83 **+8**	37

Now we are in a position to do an even swap. Consider option D and ask how much we are prepared to increase the Cost in column D, to increase the Social and Economic Impacts of column B from 66 up to 87. Suppose we are prepared to increase the Cost in column D 8 units for such an increase in column C's relevant cell. Then the relevant scores at both columns will be the same and we can eliminate them form the analysis. Then, the revised Consequences Table is:

Table 5.7 Application of Even Swaps Method (2)		
CRITERIA GROUPS	**OPTIONS**	
	Remove some or all of the contamination, and then dispose of it in purpose-built facilities for radioactive waste (B)	Further isolate the contamination by the addition of barriers (D)
Human Health and safety	44	35
Impacts on natural, physical and built environments	100	99
Amenity and quality of life	56	34+**22**
Security	45+**22**	67

Now let's suppose that the stakeholders give the same importance to Amenity and Quality of Life and Security. Again, we can do an even swap and the scores of these criteria will be the same. [(34+22) and (45+22)]. Therefore they can be eliminated from the analysis and Option B dominates Option D. So option B is clearly the preferred option.

It should be pointed out that if there is absence of objective data for a criterion, the stakeholders could simply rank-order the options. That is to say "1" would be assigned to the option which is the best on that criterion and a "2" which is the second best and so on. Then dominance analysis could be performed.

The main shortcoming of the even swap method is that it does not equalise scores on base criteria which makes it open to misuse. In addition, with the use of the practical dominance, some of the stakeholders might not be fully convince that this method is well structured. Also, it is based on micro judgments; it does not depend on the whole view of the options.

However, the even swaps method is very easy to implement and simplifies the options in a progressive ways which in turn offers transparency. This method can be easily implemented in both simple and intermediate cases. It can not be easily implemented in complicated cases due to the fact that it requires long calculations and if there are many criteria it will be much more complicated to make comparisons.

5. Analytical Hierarchy Process

AHP is based on three steps: The first step is disaggregating the decision problem in a hierarchy of levels. The aim here is to structure the weights for the criteria. The second step is the comparison of the options and the criteria. As the last step, we synthesise the comparisons to get the priorities of the options with respect to each criterion and the weights of each criterion with respect to the goal.[8] In fact AHP method calculates the weights as the elements in the eigenvector associated with the maximum eigenvalue of the matrix. However we will use a different method to avoid advanced algebra[9].

To perform AHP analysis, first let's take the performance matrix. For the sake of simplicity let's assume that there are 3 options and 3 criteria.

Table 5.8 Application of Analytical Hierarchy Process			
CRITERIA GROUPS	**OPTIONS**		
	Do Nothing (A)	Remove some or all of the contamination, and then dispose of it in purpose-built facilities for radioactive waste (B)	Immobilise some or all the contamination in the ground (C)
Human Health and safety	30	44	42
Impacts on natural, physical and built environments	32	100	90
Amenity and quality of life	45	56	55

[8] Some Prioritisation Methods for Defence Planning; Minh-Tuan Nguyen; Defence Systems Analysis Division Information Sciences Laboratory, 2003

[9] Ernest H. Forman, *Decision by Objectives,* http://mdm.gwu.edu/Forman/DBO.pdf

The next step is to form a pairwise comparison matrix A where the number in the i^{th} row and j^{th} column gives the relative importance of each of the criteria compared with each other, say B_i as compared with B_j.

Thus we might arrive at the following matrix:

$$A = \begin{bmatrix} 1 & 3 & 7 \\ 1/3 & 1 & 3 \\ 1/7 & 1/3 & 1 \end{bmatrix}$$

In order to normalize the weights, let's compute the sum of each column and then divide each column by the corresponding sum. Let's call the new matrix C.

$$C = \begin{bmatrix} 0.68 & 0.69 & 0.64 \\ 0.23 & 0.23 & 0.27 \\ 0.09 & 0.08 & 0.09 \end{bmatrix}$$

Then to determine the weights we can use geometric mean:

For criterion 1= $(1*3*7)$^1/3= 2.76
For criterion 2 =$(1/3*1*3)$^1/3= 1
For criterion 3=$(1/7*1/3*1)$^1/3= 0.36
After normalising the weights are as follows;

$$W = \begin{bmatrix} 0.67 \\ 0.24 \\ 0.09 \end{bmatrix}$$

If we place the relative weights of the criteria into the performance matrix and multiply the options' scores against the criteria we get the options' total performance. This is shown in Table 5.9:

Table 5.9 Application of Analytical Hierarchy Process (2)

CRITERIA GROUPS	Weights	OPTIONS		
		Do Nothing	Remove some or all of the contamination, and then dispose of it in purpose-built facilities for radioactive waste	Immobilise some or all the contamination in the ground
Human Health and safety	0.67	0.68	0.69	0.64
Impacts on natural, physical and built environments	0.24	0.23	0.23	0.27
Amenity and quality of life	0.09	0.09	0.08	0.09
Total (∑)	1.00	0.5189	**0.5247**	0.5017

AHP provides a solid insight to the decision making process, and a nicely structured method for determining weights in a systematic manner. However the pairwise comparisons may be quite time consuming in case there are a large amount of criteria and options. Therefore, in case there is a large of criteria, AHP is not suggested as an options comparison method.

6. Non-compensatory Methods

As stated on Chapter IV, conjunctive and disjunctive selection procedures, lexicographic ordering, and elimination by aspects are non-compensatory methods. They are quite simple to implement and do not require complicated calculations. The stakeholders have to rank the criteria from the most important to the least one and try to identify the satisfying options for that criterion. Hence these methods can be applicable to contaminated management cases. As in the dominance method these methods can be used in all the cases.

The best known non-compensatory method is Elimination by Aspects. With this method options are first ranked according to a criterion which is chosen due to its relative importance. All options below some value on that criterion are then eliminated from the choice set. This process proceeds sequentially using different criteria until all the options are ranked and a single option remains.

With the lexicographic method options are first ranked on the basis of the most important criterion. If there exists a single option showing the highest evaluation on this criterion then it is chosen, otherwise the process proceeds to the next important criterion and so on.

In contrast to the elimination-by-aspects and the lexicographic model, conjunctive and disjunctive decision rules do not involve a sequential decision making process. A conjunctive rule implies that each option which fails to meet a minimum value on each criterion will be eliminated from the choice set. The disjunctive method involves an evaluation of the options on the basis of maximum rather than minimum values on each criterion. Only options which meet or exceed at least one of these maximum values are accepted for further consideration. Conjunctive and disjunctive decision rules will therefore not generally result in unique choices, however, they can be used as the first phase of a two-phase decision process. For example, in the second phase a compensatory method or another disjunctive or conjunctive method with more stringent criteria of acceptability could be used[10].

[10] Non-Compensatory decision rules and consumer spatial choice behavior: A test of predictive ability; Harry Timmermans, *University of Technology, Eindhoven*

VI. Conclusion

Efficient decision making in environmental issues requires a structured approach which takes into consideration environmental, technological, financial and others factors. Due to the fact that each of these factors includes different criteria, the decision process is multiobjective. The stakeholders' interests sometimes coincide, however they have different priorities which can cause conflicts among the stakeholders. Therefore, in the management of contaminated lands, if the decision making process is transparent and efficient then all the parties' views will be fairly reflected in the decision. This will definitely increase the trust among the decision makers and the process will give much more opportunity to result in a consensus.

For the stated reasons, stakeholder involvement is crucial for successful environmental decision making. In the late 1990s a project was initiated to develop guidance on managing contaminated land on nuclear and defence sites which was named "SAFEGROUNDS. It develops good practice guidance on the management of radioactively contaminated land on nuclear and defence sites in the UK. The existing "Land Management Guidance" which was produced by SAFEGROUNDS sets out an overarching approach. This was developed with input from a wide range of stakeholders. However, it is not particularly specific, and there has been a recognition that more detailed advice of particular options comparison methods are very valuable. Therefore the aim of the report was to identify structured methods for decision makers that can deal with different levels of detail which are relevant to different situations.

The field of MCA incorporates methods that help develop a decision-analytic framework useful for the management of contaminated sites. With the help of MCA techniques, decision makers and stakeholders, can systematically consider and apply value judgments to reach the most valuable option. Multi criteria techniques incorporate a wide variety of approaches ranging from the highly sophisticated to the simple rating systems. The most important advantage of multiple criteria analysis (MCA) over informal judgment is its capacity to simplify complex situations. Without using structured approaches decision makers cannot take account of the totality of information into their judgment beyond a certain number of criteria. MCA breaks down the components of complex situations, and tries to find a solution in a transparent way so that the decision makers will have a good understanding over the decision making process. In addition, it is a useful negotiation tool for debates among decision makers. Therefore, using MCA techniques provides strong foundations to decision makers to make structured and transparent decisions. Also their explicit approaches result in much more efficient, reproducable and reliable decision making process as compared with the intuition and bias driven decision processes. On the other hand, different MCA methods have limitations. Some of the methods are often impossible for practical applications.

Different MCA methods have been compared in terms of deciding which method would be the most appropriate for decision making in the context of contaminated land management. Even though MCA definitely provides with valuable advantages over informal judgments, choosing a suitable MCA method requires of the careful consideration of the decision makers. Each of them has strengths and weaknesses; some of them are not easy to implement whilst others do not have clear theoretical foundations for representing stakeholders' preferences. Therefore, the main criteria in using a specific method for the contaminated land management were whether the method which is used is simple, transparent, implemented without difficulties and open to a wider range of users.

Taking into account all of the stated concerns direct evaluation of performance matrix, dominance analysis, linear additive methods, multiple criteria decision analysis, even swaps, analytical hierarchy process and non compensatory methods are suggested. These methods provide with the most meaningful approaches in terms of option comparison of contaminated land management. They are much easier when implemented, provide with much more transparency and are open to a wider range of users than the other methods. They are implemented easily because they incorporate simple methods, so every stakeholder can easily participate in the decision process.

VII. Reflective Chapter

This part of the report provides reflections on the learning experience during the project, discusses its overall success, and gives some general ideas about these kinds of projects. It also reflects experiences which can be generalized to other projects.

The project that I have undertaken was a purely Decision Science project. The sponsoring organisation's demand was to analyse different options comparison methods in the decision science field and describe how they might be applied in the context of deciding what to do with radioactive contamination in land on nuclear and defence sites in the UK. Even though during graduate study the different techniques which can be used in a decision science problem had been carefully studied this knowledge needed to be supplemented to deal with the problem. First the nature of the problems to be addressed had to be understood: contaminated land, nuclear power, and the particularly diverse issues to consider and range of stakeholders to engage. At the end of this extremely challenging learning process, an adequate appreciation of these kinds of problems was obtained. The first, and most valuable, experience gained from this project is that in consultancy one has to quickly understand the sector and its problems as well as the clients' desires. Therefore before undertaking these kinds of projects one has to research the sector and ensure that one is well briefed.

A key requirement for success is effective interaction with the sponsoring organisation. It was a great experience to work with the organisation's professionals, however they had quite different backgrounds in that they were physicists. The development of a good understanding and working relationship, despite the difference in background, was a key challenge. In our first meeting, even though the level of communication was high, it was necessary to contemplate their problem and how to solve it. But as the project progressed, the level of interaction increased and that provided a deeper understanding of the work. Ultimately, having different backgrounds did not constitute a problem but actually increased our effectiveness in dealing with the issues, in that a decision science perspective was brought to the problem. In addition, the sponsoring organisation was a small consulting firm and the culture was quite flat which enhanced the level of the interaction. I can easily say that they were quite open to every idea which definitely increased the level of interaction as well as the understanding of the problem. As a result of this high level of interaction it was possible to come up with a robust, complete and successful solution to the problem. Therefore, it was concluded that, good communication skills are absolutely a prerequisite for success in these kinds of projects, and valuable experience was gained of interacting with professionals in such situations.

A further requirement is a sound approach to the project. This started with the formulation of the problem. This was the most difficult stage of the project. The typical questions were: "Who are the stakeholders? What are the goals and values? What are the typical problems etc." During the identification of the problem many discussions and debates took place, sometimes written and sometimes oral. Once the problem was totally understood, the second phase commenced, which was the review of the available approaches. This involved working alone, using the knowledge and experience gained during studies, supplemented by a literature review. Also the academic supervisor was consulted, who provided valuable ideas. During this phase of the project preliminary documentation was prepared and discussed with the sponsoring organisation. The last phase of the project involved the assessment of the multi decision analysis techniques for suitability, by testing them with hypothetical examples of contaminated land situations. At that stage the results of the decision analysis were analysed with the sponsoring organisation. The experience gained here is of the importance of structuring one's approach to a problem and taking responsibility for a considerable degree of autonomous working, whilst appreciating when it is necessary to seek further advice.

Having mentioned the methodology used during the project, the decision problem is now discussed, including the development of solutions and the lessons learnt. As already mentioned, the problem was a decision analysis issue, but was related to a specialised field. That is where its challenge was lying. In meetings with the sponsoring organisation, they strongly pointed out their concerns about which decision technique must be used concerning different cases, and the need to identify techniques that properly suited the type of problems being considered. They already knew some of the methods and their aim was to both clarify which decision techniques should be used under which circumstances and learn of any more methods in decision science that might be suitable

Therefore the main problem was choosing the right method taking into account;

a) the stakeholder engagement level,

b) the contaminated land size,

c) the stage of planning (strategic decisions, technology decisions etc)

This problem was quite demanding as well as challenging in that there were only a few published studies that investigate the use of multiple criteria techniques to facilitate decision making for contaminated sites. Besides, these few studies were only dealing with limited methods and these methods were quite theoretical.

Another requirement for the project was determining methods that effectively enhanced the stakeholders' trust of each other. This is because in environmental decisions there are a lot of different stakeholders whose backgrounds are quite different. Some of them have difficulties to understand the decision process because of its complexity. That is why the solutions must incorporate all of the different stakeholders' understandings, as well as being readily understandable. Therefore, a second challenge in the project was to find some decision analysis techniques which satisfied all the stakeholders including the non technical ones.

Basically the problem is characterised by three cases, which are as follows:

Simple Cases: A small patch of contaminated land on a controlled nuclear or defence site, considering options for implementation, with interest of few stakeholders (management and regulators, primarily).

Intermediate Cases: A large area of contaminated land (perhaps within a site) for which an implementation technology needs to be identified, with the local stakeholder interest (management, regulators and some in the local community).

Complicated Cases: A whole site, considering strategic options, with interest of many stakeholders (management, regulators, local and some national stakeholders).

During the project, all identified techniques were assessed for their applicability to such problems and the optimal ones were systematically identified. This involved considerable discussion and debate with the sponsoring organisation.

One of the key learning points in the assessment of methods was that even though some of the decision making techniques have strong theoretical foundations, they do not contribute so much to the real life situations in that they are difficult to implement and communicate. That is one of the main lessons learnt with the project: a theory is successful as much as it helps real life problems; otherwise, the theory should evolve. The opportunity to examine the applicability of theoretical approaches to a real-life problem was a key learning experience that supplemented learning during the course. The implementation phase has provided the necessary tools for real life problems that will be experienced after graduation.

In conclusion, the success of the project must depend on how the sponsoring organisation's requirements and the outcome of the project match each other. At the end of the project, the sponsoring organisation commented as follows.

"*The work undertaken during the research project has provided a valuable foundation for our project to provide guidance on options comparison methods suitable for the management of contaminated land on nuclear and defence sites. It has added theoretical rigour and insight to complement our practical experience, giving our document important credibility. The outcome will be guidance that will certainly lead to better practical decision-making in a very important field of environmental safety*."

The successful conclusion of the project will therefore contribute to increasing the effectiveness of decision making in these situations.

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ANNEX

1. Terms of reference.

APPENDIX A

Examples of the Methods which are not used in the Management of Contaminated Land

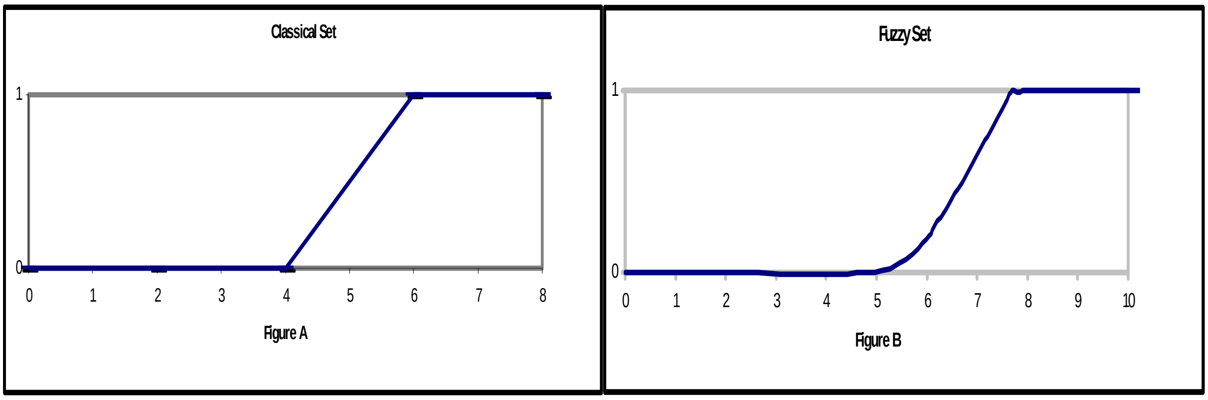
Fuzzy MCA[11]

A is a classical set and μa *(x) is a set membership function associated with it. It is defined by;*

$$\mu_A \equiv \begin{cases} 1 \text{ if } x \in A \\ 0 \text{ if } x \notin A \end{cases}$$

As seen, μA (x) can take the values 0 or 1. However, in case we allow ambiguity, then μA (x) can take any value between 0 and 1. "*For instance, consider the set of tall men. Under classical set theory we should have to define a precise height, say 6 ft, above which a man would be tall and below which not tall. Thus the set membership function would have the form shown in Figure a below. However, if we admit that tallness is a much vaguer concept, then we might feel that the set membership function shown in Figure b would be more appropriate. Fuzzy set theory formalizes this notion. A fuzzy set is a real-valued function that takes values in the unit interval. This function is called the set membership function.*

Figure IV-7. Set membership functions for the set of tall men.



Multi Attribute Utility Theory[12]

Let's assume that there is a set of options to choose. Subjective Expected Utility function will be:

$$U_i = p_1 u_{i1} + p_2 u_{i2} + \ldots\ldots\ldots\ldots\ldots + p_n u_{in} = \sum_{j=1}^{n} p_j u_{ij}$$

Where:
U_i = the overall utility (preference score) of option *i*;
u_{ij} = the utility of option *i* if, having chosen option *i*, it subsequently transpires that state of the world *j* occurs;
p_j = the decision maker's best judgement of the probability that future state of the world *j* will occur.

[11] A Multi-Criteria Decision-Making Method for Solar Building Design, Inger Andresen Norwegian University of Science and Technology Faculty of Architecture, Planning and Fine Arts Department of Building Technology.
[12] DETR Multi-criteria analysis manual, John Dodgson, Michael Spackman, Professor Alan Pearman and Professor Larry Phillips

It is beyond the scope of this report to provide with the procedures for calculating u_{ij} estimates, which can be relatively complex. For example determining the functional form as well as estimating the parameters with only two or three criteria is a very complex issue and the stakeholders will not feel comfortable with that MCA method. However as stated before, MAUT has strong theoretical insigths and it is suggested that it can be usually applied to problems where uncertainty level is high.

Multi Objective Decision Making

This method is a classical example of linear programming. In linear programming, the objective is always to maximize or to minimize some linear function of the decision variables.
Let's consider an objective function such as;

O= $c_1 x_1 + c_2 x_2 + \dots\dots\dots + c_n x_n$

Our objective is to maximise this function. However with these kinds of problems there are always some constraints:

$$a_1 x_1 + a_2 x_2 + \dots\dots\dots + a_n x_n \begin{Bmatrix} \leq \\ = \\ \geq \end{Bmatrix} b$$

Hence the linear programming problem can be formulated as follow:

Maximise $c_1 x_1 + c_2 x_2 + \dots\dots\dots + c_n x_n$

Subject to

$$\begin{aligned} a_{11} x_1 + a_{12} x_2 + \dots\dots\dots + a_{1n} x_n &\leq b_1 \\ a_{21} x_1 + a_{22} x_2 + \dots\dots\dots + a_{2n} x_n &\leq b_2 \\ \vdots \quad \vdots \quad & \quad \vdots \quad \vdots \\ a_{m1} x_1 + a_{m2} x_2 + \dots\dots\dots + a_{mn} x_n &\leq bm \\ x_1, x_2, \dots\dots\dots, x_n &\geq 0 \end{aligned}$$

As seen, MODM methods are not so applicable because of their complicated mathematical forms.

ELECTRE

Among many existing methods ELECTRE (Elimination Et Choix TRaduisant la rEalité) consists in the computation of two matrices named "Matrix of Concordance" and "Matrix of Discordance". These matrices can be used directly for ranking the options or be compared with some predefined "threshold values" (weak dominance) of concordance or discordance. They also can be used for computing absolute indicators of concordance and discordance.

Concordance Index: Suppose there are two options a and b. The concordance value of a with respect to b is the sum of the criteria weights for each option score of a > b. Therefore the mathematical expression can be written;

$C_{ab} = \{j / z_{ja} > z_{jb}\}$
where:

C_{ab} = concordance value of project a with respect to b
j = all criteria j
Z_{ja} = all criteria j of option a
Z_{jb} = all criteria j of option b

Similar to the concordance index, the discordance index is constructed by comparing single pairs of options. The discordance value of project a with respect to project b is calculated as the ratio of the highest difference between the options scores of project b and those of project a and the maximum observed difference in score on the criterion concerned between any pair of options in the set being considered[14]. In Contrast to the concordance index, weights are not required here. Also if option a performs better than option b on all the criteria then the discordance index is zero.

The mathematical expression will be complementary to the concordance matrix:

$D_{ab} = \{j/z_{ja} < z_{jb}\}$

Having prepared these two matrices, it is possible to proceed with the ranking of projects on the basis of the "weak dominance" approach. The weak dominance approach requires that two thresholds be defined: the concordance threshold (CT) and the discordance threshold (DT). The option a will dominate the option b if its concordance value is higher than the CT and its discordance value is lower than the DT. If more than one option respect the above rule thresholds will be changed (CT will be decreased and DT increased) up to the point were only one option dominates the others.

As seen, ELECTRE is essentially related to identifying dominance. However, the complex arithmetical operations make it difficult to implement. As mentioned before, in case there are lots of options and criteria, this method is not easy to implement and requires repetitive numerical calculations. Therefore, as stated in DETR manual MCDA process is better suited to a broad range of public decisions.