EUROPEAN COMMISSION

Community Research

SEVENTH FRAMEWORK PROGRAMME

CARBOWASTE

Treatment and Disposal of Irradiated Graphite and Other Carbonaceous Waste

Grant Agreement Number: FP7-211333

Deliverable (T-1.4.1)

- Review of MCDA Tools/Methodologies Previously Employed and Relevance to this Project -

Author(s): **David N Ross**

……………………………

Reporting period: e.g. 05/2008– 03/2009

Date of issue of this report : 17/04/2009

Project co-funded by the European Commission under the Seventh Framework Programme (2007 to 2011) of the European Atomic Energy Community (EURATOM) for nuclear research and training activities		
Dissemination Level		
PU	Public	
RE	Restricted to the partners of the CARBOWASTE project	
CO	Confidential, only for specific distribution list defined on this document	X

Start date of project : **01/04/2008** Duration : **48 Months**

Distribution list

Person and organisation name and/or group	Comments
CARBOWASTE Partners	For information

CARBOWASTE		
Work package: 1 **Task: :** 1.4	**CARBOWASTE document no:** CARBOWASTE-0904-T-1.4.1 (e.g. May 2008 as date of issue: 0805)	**Document type:** **D=Deliverable**
Issued by: NNL (UK) **Internal no.:** NNL (08) 9842 Issue 2		**Document status:** **Final**

Document title
Integrated Waste Management Approach WP 1 Summary Report
Executive summary

The CARBOWASTE Project is concerned with the development of best practices in the retrieval, treatment and disposal of irradiated graphite (i-graphite) including other i-carbonaceous wastes.

The CARBOWASTE Project is not intended to identify a single EU disposal option, but to produce a unified approach that will allow each i-graphite management route to meet its own criteria and authorisation requirements.

Multiple criteria affect the selection of the best route for each waste stream. A method of rationally selecting between multiple options, each with different strengths and weaknesses, is therefore required.

Towards this end a number of pieces of work have been commissioned. The first, presented here, reviews potential techniques for supporting decision making using Multiple Criteria Decision Analysis (MCDA) tools. Subsequent reports will identify criteria by which options will be assessed and will identify the most appropriate MCDA techniques to be applied to assist in selecting the best management option for a given waste stream using these criteria.

There are a very large number of MCDA tools and techniques reported in the literature. This report is kept to a manageable size by drawing heavily on a number of previous reviews of decision-making tools and techniques. Several of these have been carried out at national and European levels. The report then describes the MCDA tools and techniques that are prominent in use and in the literature, starting with the most basic 'elementary' techniques and progressing to the more sophisticated and flexible methods.

The inherent strengths and weaknesses of the main methods are discussed. There are a range of techniques which are suitable for deployment on the CARBOWASTE project, depending on the precise application, and these will be considered further in the next phase of work.

Revisions						
Rev.	Date	Short description	Author	Internal Review	Task Leader	WP Leader
00	dd/mm/yyyy	Issue	Name, Organisation	Name, Organisation *Signature*	Name, Organisation *Signature*	Name, Organisation *Signature*
	23-12-2008	Issued as NNL (08) 9842 Issue 1	Ross, D N NNL	Jarvis, R B Whitton, J NNL	Banford A, Eccles H NNL	Banford A, Eccles H NNL
01	17/04/2009	1st issue	Ross, D N NNL	Jarvis, R B Whitton, J NNL	Banford A, Eccles H NNL	Banford A, Eccles H NNL
				R Jarvis	AWB	AWB

Glossary

AHP	Analytical Hierarchy Process
BEACON	Building Environmental Assessment Consensus
BPEO	Best Practicable Environmental Option
CBA	Cost-Benefit Analysis
CEA	Cost-Effectiveness Analysis
CIFOR	Centre for International Forestry Research
CLARINET	Contaminated Land Rehabilitation Network for Environmental Technologies
CoRWM	Committee for Radioactive Waste Management
COWAM	Co-operative Research on the Governance of Radioactive Waste Management
DG TREN	Directorate–General for Energy and Transport
DoE	(U.S.) Department of Energy
ELECTRE	Elimination et Choix Traduisant la Réalité
EPA	(U.S.) Environmental Protection Agency
EURATOM	European Atomic Energy Community
GAIA	Geometrical Analysis for Interactive Aid
GIS	Geographic Information Systems
LCA	Life Cycle Assessment/Analysis
MADA	Multi-Attribute Decision Analysis
MADM	Multi-Attribute Decision Making
MAUT	Multi-Attribute Utility Theory
MCA	Multi-Criteria Analysis
MCDA	Multi-Criteria Decision Analysis
MODM	Multiple Objective Decision Making
NAIADE	Novel Approach to Imprecise Assessment and Decision Environments
NNL	National Nuclear Laboratory
PROMETHEE	Preference Ranking Organisation Method for Enrichment Evaluation
RES	Renewable Energy Sources
SEA	Strategic Environmental Assessment
SMART	Simple Multi-Attribute Rating Technique
SWOT	Strengths, Weaknesses, Opportunities and Threats
TOPSIS	Technique for Order Preference by Similarity to the Ideal Solution
V/HTR	(Very) High Temperature Reactor

1 Introduction

The disposal of irradiated graphite (i-graphite) from numerous graphite moderated reactors worldwide presents a significant challenge to all stakeholders. The number of graphite moderated reactors that have been part decommissioned i.e. inclusive of graphite retrieved, is small - no more than three (two in the UK and one in the US). Even for this small number of reactors the decommissioning is incomplete since, in two cases, the retrieved i-graphite is awaiting final disposal.

In the EU a specific project, CARBOWASTE[1], is addressing i-graphite waste management and will consider a variety of options for retrieval, treatment and final disposal. These options will be judged using Multi Criteria Decision Analysis (MCDA).

This review of previously published information discussing MCDA is the first step in selecting an appropriate model/technique to be employed in the CARBOWASTE project. The review has also been prepared to provide some background information initially for other CARBOWASTE WP 1 participants, but will ultimately be distributed to all participants.

1.1 Terminology

The terminology used in the field of decision-making methodologies can be confusing with different terms being used interchangeably in the literature. For clarity, wherever possible, Multi-Criteria Decision Analysis (MCDA) is used in this review in preference to Multi-Criteria Analysis (MCA) or Multi-Attribute Decision Analysis (MADA).

There are a number of definitions of MCDA in the literature; one definition[2] describes MCDA 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…"
Trade-offs between options can, for example, be between costs and benefits and between short and long term benefits/risks. The aim is to aid decision making, not to take the actual decision itself.

1.2 Background

The National Nuclear Laboratory (NNL) is involved in the European Atomic Energy Community (EURATOM) FP 7 project that involves 27 other participants. The objective of the CARBOWASTE project is the development of best practice in the retrieval, treatment and disposal of irradiated graphite (i-graphite) including other i-carbonaceous waste such as structural material made of graphite, non-graphitised carbon bricks and fuel coatings (pyrocarbon, silicon carbide). It addresses both existing legacy waste as well as waste from graphite-based nuclear fuel resulting from a new generation of nuclear reactors (e.g. V/HTR).

The NNL as leader of Work Package 1 (WP1) is responsible for:

- defining the various targets (end points) for an integrated waste management approach;
- development of a route map and analysis of the key stages of the route map (i.e. from in-reactor storage to final disposal) with regard to the most economic, environmental and sustainable options.

This methodological approach will enable Member States to select the most appropriate options to meet their specific criteria and considerations. Emphasis will therefore be given to legacy i-graphite as this currently represents a significant problem that will have to be addressed in the short and medium term.

This route map and critical decision analysis is crucial to the success of this project and has not been used in this arena previously. The two key major states within the road map are the current disposition of i-graphite, i.e. largely in the redundant reactor, and its final disposal. Use of criteria decision analysis proposed by the NNL MCDA is one of the cornerstones of the CARBOWASTE submission to the EURATOM's Research and Training Framework 7 Programme, 1st Call.

WP1 represents the 'Strategic Optioneering' for the whole project and so must identify economic, ecological and licensing requirements for i-graphite waste management. The selection of retrieval, treatment and disposal options will have to be guided by Member State targets (end points).

The approach proposed by this work package, combined with information drawn from the other five work packages, will then allow:

- selection of disposal processes and repository conditions;
- Multiple criteria comparisons of a base case option (such as disposal of all retrieved materials as encapsulated waste), to other options developed in this project;
- Sensitivity analysis of project decisions to changes in input data.

1.3 Purpose of this report

This report provides a summary of MCDA techniques, with the aim of providing a 'tool box' of clearly defined assessment options for the project. The approach is not intended to identify a single EU disposal option, but to produce a tool box of MCDA techniques that will allow each i-graphite management route to meet its own criteria and authorisation requirements.

The selection of the most appropriate MCDA approach for the Carbowaste project will be the subject of a companion study (due March 2009). Dedicated software systems have been developed to support many of these methods; these are not discussed in this document but will be included in the final assessment/selection.

The MCDA Assessments for selection of retrieval, treatment and disposal options are currently programmed for 2010-11.

2 Decision-Making Methodologies

2.1 Introduction

Different MCDA approaches all follow the same basic approach shown below (adapted from [2], [3] and [4]), although some of the steps e.g. weighting are not always carried out.

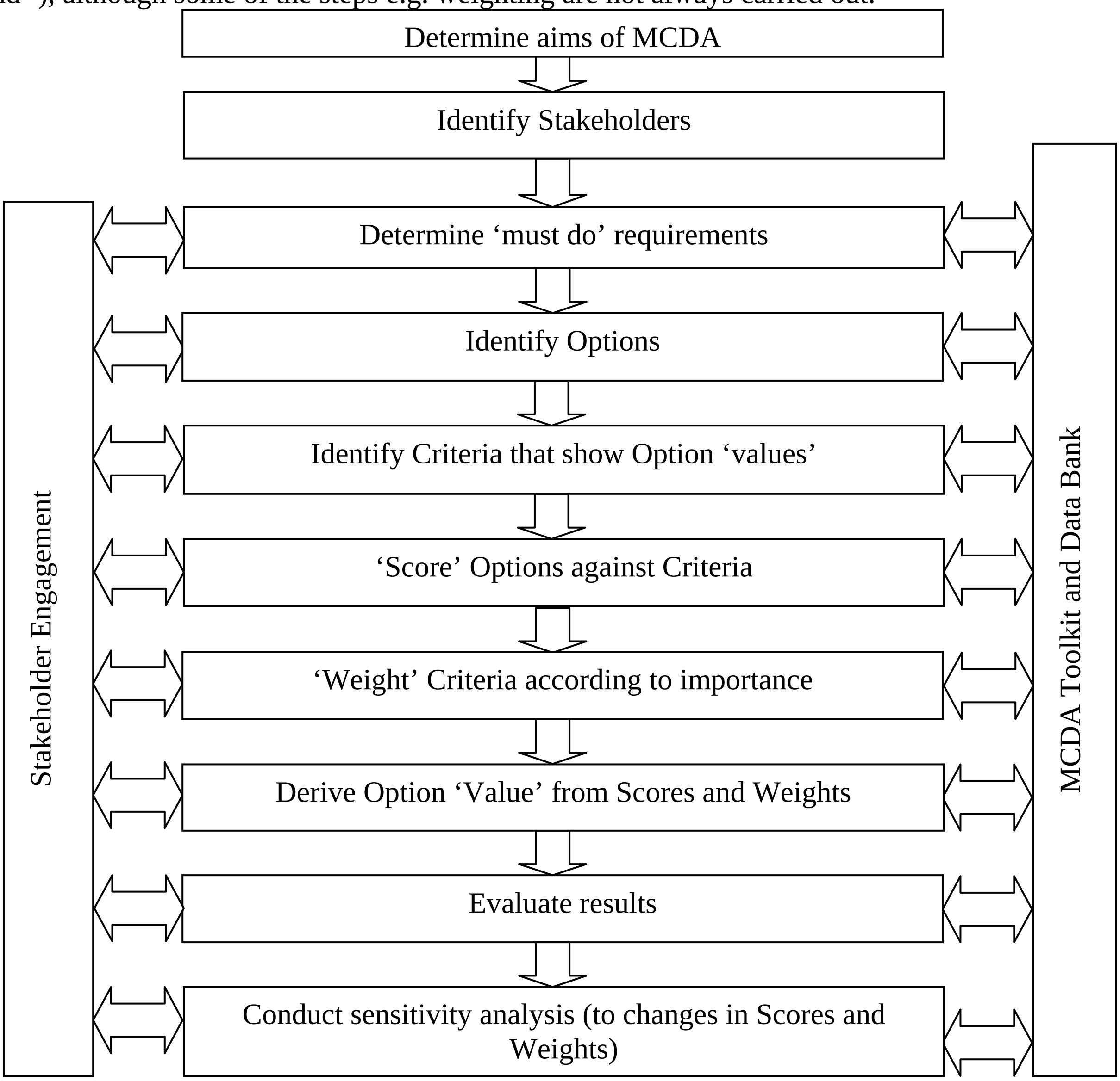

Figure 1 Generic Decision-Making Process

Once the aim of the MCDA has been defined, the decision-making process then moves to establishing who is going to make the decision and who the stakeholders are in the decision. Stakeholders should be engaged throughout the process, particularly in the early process stages, so that their views can be captured.

The next step is to define the 'must do' requirements. Certain options may be eliminated during the decision-making process simply because these fail to meet essential criteria e.g. an upper cost limit.

Options may be pre-determined e.g. when considering different technologies to tackle a problem, or may need to be determined. In the latter case, this is typically undertaken by the decision-making team. When defining options it is important to state how each tackles the problem and what distinguishes it from other options. It is important that the start point and end point for each of the options is the same.

Criteria against which the options are to be evaluated should be carefully defined, and be:

- Discriminatory between options
- Comprehensive
- Relevant
- Not repeated
- Manageable in number

The MCDA technique to be deployed needs to be determined at this stage because the scoring and weighting methods depend on the selected method.

Scoring of options against criteria is a means of defining the performance of the option against each criterion; weighting of each criterion allows the decision-making team to communicate the relative importance of the criteria with respect to each other.

The scoring and weighting of options can be performed using a mix of quantitative data and qualitative information. How these different types of quantities are compared and/or combined depends on the MCDA method chosen.

Evaluation of results may be a straightforward comparison of option scores; however it may also entail calculation of option scores per unit cost, or other assessment of the results. Sensitivity analysis is used to establish the impact of uncertainty in scoring and so provides a method by which the significance of differences between "values" can be determined. Sensitivity to both scores against the criteria and weights applied should be performed. A sensitivity analysis will allow the robustness of the MCDA output to be demonstrated.
The flow of Figure 1 is from top to bottom, but in reality it is not uncommon for earlier steps in the process to be re-visited in the light of new information or technologies. The decision-making team may utilise facilitation for the key steps to ensure that the process is followed correctly and that the rationale behind weighting and scoring is recorded in a transparent manner.

Rigour in following the process is important to ensure that the MCDA output can withstand challenges of being:

- biased toward particular stakeholders;
- simply a back-fit to an already determined solution.

2.2 MADM and MODM

There are two main classes of multi-criteria decision problems[5] Most decisions concern choices between a finite number of options, the details of which have already been pre-determined before they are subject to MCDA. This does not exclude the possibility that, following MCDA, the decision-making group may use insights from the MCDA, coupled with expertise from other sources, to re-define some options and run the MCDA again. The basic MCDA method itself is not used to redefine the options. It is simply used to assess the strengths and weaknesses of options as they stand and is often known as Multi-Attribute Decision Making (MADM).

There is also a second class of problems where the MCDA methods themselves, sometimes using interactive computer programs, directly seek to specify what the best option should be. The question is essentially one of identifying an optimal design for the option, guided by MCDA methods. Almost always, the optimisation is subject to specific constraints, for example on cost or technical specification. Problems of this type, where the decision variables are infinitely variable, subject to constraints and where there are multiple objectives, are often called multiple objective decision-making problems (MODM). MODM is not discussed further in this document as the challenge within the CARBOWASTE project is to focus on selection from a finite number of clearly defined alternatives, comparing against set criteria.

This review focuses on MCDA techniques which are classified as MADM as they are concerned with selection from a finite number of options. The relationship between MADM, MODM and the specific MCDA techniques discussed in this review is illustrated in the following schematic:

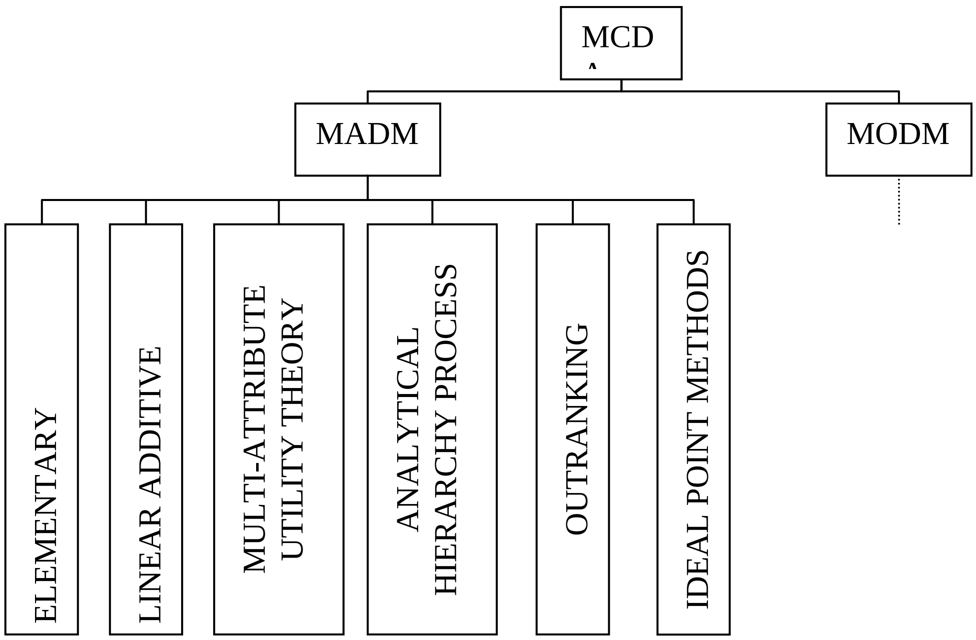

Figure 2: Relationship between MCDA, MADM and MODM

3 Previous Reviews and Case Studies

3.1 Reviews

There are a number of reviews available in the literature which contrast and compare the various MCDA, and related, decision-making tools and techniques.

It has not been practicable in this preliminary review to provide a detailed description of all of the methodologies referred to below. The reader is referred to the appropriate references should further detail be sought. The primary focus in this review has been on the key features of the principal MCDA techniques from which the ultimate decision-making methodologies will be selected for the CARBOWASTE project.

In the following sections the principal MCDA methods are outlined and discussed. In doing so, use of mathematical expressions has been avoided to ensure that the underpinning principles of the techniques are clearly communicated.

The most relevant reviews of MCDA techniques are described in Section 3.1.

A small number of selected Case Studies are outlined in Section 3.2

Individual techniques are described in Section 5.

3.1.1 SEA (BEACON)

The European Commission have produced a Manual to support the Strategic Environmental Assessment (SEA) Directive in the field of Transport Infrastructure Plans and Programmes through the Building Environmental Consensus (BEACON) Programme; this Manual is in turn supported by Fact Sheets, the first of which[5] describes the following impact assessment tools:

- Cause Effect Modelling
- Screening – Ecological Risk Assessment Tools
- Transport Forecast Models
- Coupled land use/transport models
- Calculation of emission and exposure
- Cost Benefit Analysis
- Life Cycle Assessment
- Intelligent GIS
- Decision Support Tools MCA
- Information Sharing, Group Decision Taking and Public Involvement Tools

3.1.2 CLARINET

Also supported by the European Commission is the Contaminated Land Rehabilitation Network for Environmental Technologies (CLARINET). Under the CLARINET project a review of decision support tools for contaminated land management, and their use in Europe was undertaken[6]. The review presents results on a country by country basis. This review discusses a wide range of approaches and discusses the following Decision Support Tools in detail:

- Environmental Risk Assessment
- Multi-Criteria Analysis/Multi-Attribute Techniques
- Cost Benefit Analysis/Cost Effectiveness Analysis
- Life Cycle Analysis

3.1.3 COWAM-2

COWAM-2 (Co-operative Research on the Governance of Radioactive Waste Management) is a research project that brought together over the course of three years a diverse group of stakeholders, to investigate the range of governance issues in radioactive waste management. Full details are presented in the final report[7] which was published in 2008.

The COWAM-2 project comprised four thematic co-operative research groups. Each group liaised with thirty local and national stakeholders six times over the course of the project, supported by research contractors with the task of documenting and developing the research outcomes.

The group on “quality of the decision-making process” (Work Package 3) developed recommendations for implementing a robust decision-making process or for judging an existing decision-making process. The recommendations took the form of propositions to assist stakeholders in making decisions or evaluations.

3.1.4 MCDA-RES

The Directorate–General for Energy and Transport (DG TREN) of the European Commission, under the Energy Programme (5th Framework), co-financed and supported a project entitled “Development and Application of a Multi-Criteria Software Decision Analysis Tool for Renewable Energy Sources” (MCDA RES) which was undertaken by an international consortium led by the University of Aegean.

The aim of the project was to develop a Software Decision Tool that would enable the Multi-Criteria Decision Analysis of RES investments and apply it to case studies. Secondary objectives were to:

- promote RES in isolated regions under distributed generation and deregulated energy markets;
- map social preference of stakeholders in an energy-environment-economy framework;
- eliminate uncertainties and risk of new technologies;
- assist with environmental protection and emission reductions;
- encourage creation of new skilled jobs;
- invigorate the EU's RES manufacturing industry;

- reduce oil imports;
- demonstrate innovative methodological solutions and their integration in realistic operating conditions;
- enhance the security and diversity of energy systems in isolated areas;
- enable local authorities, non-governmental organizations, central government, etc. participating in Group Decision Analysis for RES investments;
- promote internet-based exchange of technical and other expertise in RES applications.

The MCDA-RES project reported their findings in 2004[8], having implemented an on-line MCDA tool box and established a data set for users. The tool box was applied to seven renewable energy case studies, in Finland, France, New Zealand, Greece and Italy.

The four MCDA techniques included in the tool box were:

- ELECTRE III
- PROMETHEE II
- NAIADE
- REGIME

3.1.5 SEA (Development Co-operation)

The Organisation for Economic Co-operation and Development (OECD) has produced a Good Practice Guidance Document[9] in applying Strategic Environmental Assessment in development co-operation. This guidance discusses the following tools for analysing and comparing options:

- Cost Benefit Analysis
- Scenario Analysis/Sensitivity Analysis
- Multi-Criteria Analysis (MCA)
- Opinion Surveys
- Risk Analysis or Assessment
- Vulnerability Analysis

3.1.6 Contaminated Site Remediation

There are reviews which attempt to define the most common approaches to contaminated site remediation on a world-wide basis. Reference[4] for example considers Multi-Criteria Decision Analyses in the context of a framework for structuring remedial decisions at contaminated sites. This review considers the techniques and also their application within:

- U.S. (DoE)
- U.S. (EPA)
- European Union

Specific examples within a number of other countries world-wide are also identified.

3.1.7 Decision-Making Methods Guidebook

A Guidebook to Decision-Making Methods has been prepared for the U.S. Department of Energy[3]. This report recommended selection from the following techniques:

- Pros and Cons Analysis
- Kepner-Tregoe Decision Analysis
- Analytical Hierarchy process (AHP)
- Multi-Attribute Utility Theory (MAUT) including the Simple Multi-Attribute Rating Technique (SMART)
- Cost-Benefit Analysis

3.1.8 CIFOR

Some very useful guidance material on selection of techniques is presented in the context of the particular decision-making problem; see for example[10] which, in the context of sustainable forest management. The Centre for International Forestry Research (CIFOR) has developed guidelines for applying multi-criteria analysis to the assessment of criteria and indicators. In this, they consider:

- Ranking and Rating
- AHP and Pair-wise comparisons

3.1.9 Communities and Local Government Department Multi-Criteria Analysis Manual (U.K.)

Within the UK, the primary reference for selection of multi-criteria analysis tools and techniques is to be found in guidance provided by the (former) Department for Transport, Local Government and the Regions (now Communities and Local Government Department)[2]. This multi-criteria analysis manual considers a wide range of techniques and their application, including:

- Monetary and non-monetary techniques
- Continuous MCA models
- Non-compensatory methods
- Multi-attribute utility models
- Linear additive models
- The Analytical Hierarchy Process
- Outranking methods
- ‘Fuzzy’ MCA

3.2 Case Studies

3.2.1 Nuclear Licensed Sites (U.K.)

Decision-making methodologies have been applied within the UK nuclear industry, for example in the context of Best Practicable Environmental Assessment (BPEO) Studies, required under the Radioactive Substances Act Authorisations for nuclear licensed sites. The MCDA/MADA technique has been widely deployed within the U.K. nuclear industry; see for example[11] which discusses the experience to date.

One of the most extensive studies[12] in this field was undertaken by the Committee for Radioactive Waste Management (CoRWM). The Committee were asked by the U.K. Government in 2003 to make recommendations for the long-term management of the UK's higher activity wastes that would protect both the public and the environment, and inspire public confidence. Multi-Criteria Decision Analysis was used to conduct a thorough performance assessment of its short-listed options for the entire waste inventory, against a number of criteria. It complemented this with a holistic assessment of the options, and compared the outcomes of the two assessments.

3.2.2 Radioactive Waste Disposal (Belgium)

An Evidential Reasoning approach for multi-criteria decision analysis, with the support of its software implementation, Intelligent Decision System (IDS), was used to analyse whether low level radioactive waste should be stored at the surface or buried deep underground in the territory of the community of Mol in Belgium[13].

In[13] it is argued that the Evidential Reasoning approach is different from most MCDA approaches in that it is designed to allow uncertainties in input data to be explicitly assessed and so to influence decision making.

3.2.3 Red Impact Project (EU)

There have been significant deployments of decision-making methodology at a European level within the nuclear industry; see for example the 'Red impact' project[14] which assessed the impact of partitioning, transmutation and waste reduction technologies on the final nuclear waste disposal.

4 Theoretical Foundations

MCDA methods evolved as a response to the observed inability of people to effectively analyse multiple streams of dissimilar information. There are many different MCDA methods. They are based[4] on different theoretical foundations such as optimisation, goal aspiration, or outranking, or a combination of these. The section below provides a summary of the principles underpinning the more sophisticated and powerful MCDA techniques, focusing on the key features of each.

Elementary techniques (Section 5.1) sometimes adopt basic elements of optimisation, goal aspiration or outranking, whereas others are based on basic elimination or visual presentation techniques.

4.1 Optimisation

- Uses scoring of options on a single common scale which needs to be determined beforehand.
- Good performance on some criteria can compensate for poor performance against others.
- Options are scored against each criterion then aggregated into a total score which reflects overall performance.
- Research continues on multi-criteria optimization. This work included studies on identifying the so-called “Pareto frontier”, along which no further improvements can be made in performance against any of the criteria without adversely affecting performance against the other criteria[15].

4.2 Goal aspiration

- Uses comparison with pre-determined performance thresholds for each criterion
- Options which exceed or are closest to these thresholds are scored accordingly
- When it is not possible to meet all thresholds the solution can be found through the optimisation approach referred to above, through either:
  - minimising shortfalls between performance and threshold
    or
  - meeting as many threshold levels as possible
- When multiple options meet all thresholds then optimisation may be used to select between feasible candidates.

4.3 Outranking

- Compare performance of two or more alternatives at a time for each criterion
- Ascertains preferred option through, for example, better performance against the largest number of criteria
- Avoids the limitations of group evaluation of a number of options with significant numbers of criteria, at the same time
- Does not need common units across criteria for scoring
- Employs a variety of techniques for:
  - Ranking of options
  - Determining a single, preferred option
  - Eliminating options

5 Multi-Criteria Decision Analysis Techniques

This section provides a summary of MCDA techniques, focusing on the key features of each.

5.1 Non-Compensatory 'Elementary' Techniques

These MCDA techniques are utilised when each option is evaluated against a common set of criteria. 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. Non-compensatory evaluation severely restricts the extent to which, in practice, overall preferences between options can be established. The following information has been derived from references[2] and [4].

5.1.1 Dominance

The dominance approach is a simple form of outranking in which one option is said to dominate another if:

- it performs at least as well on all criteria

  and
- is better on at least one criterion

If option A dominates option B, then option B cannot be the preferred option overall. If option A dominates option B and option B dominates option C then option A is said to dominate both options B and C.

The use of non-compensatory dominance methods in isolation is uncommon. However it may be used as a preliminary screening step because options dominated by all others can be screened out at an early stage in the decision-making process.

5.1.2 Conjunctive and Disjunctive selection

Conjunctive and Disjunctive approaches use simple screening methods to select a sub-set of alternatives for further consideration from an initially larger set of options:

- Uses pre-set thresholds of performance (benchmarks) for one or more criteria.
- Options that fail to reach these set performance levels are eliminated (conjunctive model).
- Conversely, options that meet set performance levels are passed through to the next stage of evaluation (disjunctive model).
- The setting of benchmarks prioritises certain criteria.

5.1.3 Lexicographic Ordering

The Lexicographic method is essentially a sequential elimination process:

- Criteria are initially ranked in order of importance.
- The alternative with the best performance on the most important criterion is chosen.

- If there is a tie, then the second most important criterion is used for comparison purposes. Again, if there is a tie the process moves onto the third criterion, and so on until a single best option is identified.

5.1.4 Elimination by Aspects

This model combines elements of both lexicographic ordering and the conjunctive/disjunctive models:

- Options are compared against a threshold.
- Criteria are examined one by one in perceived order of likelihood of maximising the number of options that fail to pass. This process is continued until only one option remains.
- For each criterion, options which do not pass the threshold are eliminated.

5.1.5 Pros And Cons

Pros and Cons Analysis is a qualitative comparison of the qualities (Pros) and defects (Cons) of options. There are two basic approaches:

- Identify a generic list of pros and cons and evaluate options against this

  or
- Identify the pros and cons of each option in turn

The alternative with the strongest pros and weakest cons is selected. There are other methods based on the Pros and Cons approach, for example:

- Strengths, Weaknesses, Opportunities and Threats (SWOT).
- Force-Field Analysis in which comparison is made of the forces for, or against, an approach.

5.1.6 Maximin and Maximax Methods

These methods require criteria to be measured on a common scale. In the Maximin approach, options are ranked by their performance against their lowest scoring criterion. The preferred option is the option with the highest score on the lowest scoring criterion. Other options are ranked accordingly.

Conversely, The Maximax approach ranks options by the score on their highest scoring criterion.

5.1.7 Decision Tree Analysis

The principle behind decision tree analysis is the linking of consequences to decision nodes. Simple models can readily be prepared using this method where sufficient quantitative data is available. More complex evaluation with multiple criteria can become unwieldy in practice due to the size of the diagrams.

On the tree the consequences of different decision paths can be mapped out and are used to show the benefits, and risks, associated with a particular decision.

5.1.8 Influence Diagrams

Graphical representation of decision-making can be useful; Influence Diagrams are used to illustrate criteria, information flows and dependencies between criteria. The criteria are represented by nodes on the diagram. Arrows between nodes show the information flows.

Influence diagrams can be used to show how decision-making problems are perceived by different stakeholder groups.

5.2 Linear Additive Methods

Linear Additive Models are a form of optimisation which has been in widespread use for many years; their suitability for deployment on a wide range of problems and circumstances is evident[2].

The method can be distilled down to the following essential steps:

- Decide on the scoring system and scale (typically between 0 and 100); typically higher scores reflect better performance.
- Determine weighting factors e.g. between 1 and 10, and ascribe weightings to each criterion.
- The levels of performance for the two reference points (0 and 100) are determined. In a global scale model the scores of 0 and 100 are associated with the worst and best performances that could be encountered in any circumstances whereas in a local scoring model the low and high performance limit are derived from the scope of the current problems for which a range of options are being considered. Global scaling allows for the ready introduction of new options but it can be difficult to define the absolute performance limits for a number of criteria.
- In some cases imposing intervals on the scoring scale e.g. 0-10, 10-20 , 20-30… can facilitate scoring; noting the limitation that a score of 30 is not necessarily 3 times better in performance terms than a score of 10.
- For each option, allot a scoring value against the criterion.
- In the linear approach the option's score against each criterion is multiplied by the weighting attributed to that criterion and then the weighted scores are added together to derive an overall score for the option.

For the model to provide reliable outputs with the simple additive approach, criteria need to be independent of each other. Uncertainty is not formally built into the approach, but can be introduced through a second stage of sensitivity analysis.

Where quantitative data is not available from which to derive a criterion score, direct rating is used. Direct rating is based on subjective scoring to derive a value for the criterion on the 0 - 100 scale.

One specific form of the linear additive approach is the Kepner-Tregoe Decision Analysis method[3]. Each criterion is scored in terms of relative importance to the other criteria (1 =lowest, 10 = highest) to determine the relative criteria weights. A total score for an option is determined by multiplying the score for each criterion by the criterion weight and then summing across all criteria. The highest scoring option is preferred.

5.3 MAUT/SMART

Multi-Attribute Utility Theory (MAUT) is a quantitative comparison optimisation method used to combine dissimilar measures of costs, risks, and benefits, along with individual and stakeholder preferences, into high-level, aggregated preferences[2, 4].

The MAUT method is used for complex decisions with multiple criteria and options.

There are three essential components in Multi-Attribute Utility Theory (MAUT). These are:

- Derivation of a performance matrix within which each row describes an option and each column the performance of options against each criterion.
- Determination of whether criteria are independent of each other or not; if not independent, what the relationship between criteria is.
- Derivation of a utility function which converts a criterion’s basic quantitative value (or the analyst’s qualitative ‘valuation’) into a utility score between 0 and 1 (this can be highly non-linear). Uncertainty can be taken into account and thereby built into the model through deriving the utility function.

The approach then follows that of the linear additive method described above. The option’s score against each criterion derived from the utility graph are multiplied by the criterion weighting. The weighted scores are added together to derive an overall score for the option. The highest scoring option is preferred.

The complexity of the MAUT model derives from two main sources:

- The integration of uncertainty into the model
- The potential for inter-dependencies between criteria

The Simple Multi Attribute Rating Technique (SMART) is a simplified version of MAUT. Instead of utility functions/graphs, the method uses multi-point scales (typically 5, 7 or ten point). In this method, options which are not significantly different in performance terms for a criterion can be given an equal score.

5.4 Analytic Hierarchy Process (AHP)

The Analytical Hierarchy Process (AHP) is a quantitative comparison method, incorporating elements of outranking and optimisation, which identifies a preferred option by using pair-wise comparison of alternatives based on the relative performance against set criteria[3]. The basis of this technique is founded on the premise that people are more capable of making judgements which are relative rather than absolute.

Like many other MCDA methods, the Analytic Hierarchy Process (AHP) develops a linear additive model, but, in its standard format, uses procedures for deriving the weights and the scores achieved by alternatives which are based, respectively, on pair-wise comparisons between criteria and between options. The following steps are used:

- Normalised weights are derived by comparison of pairs of criteria. The decision-maker is asked to determine the relative importance of the criteria.
- Pair-wise comparisons are made using a nine-point scale between 1 (options equal) and 9 (one option greatly superior) If for example criteria A is deemed to be strongly preferred to B then A is given a weight of 5 relative to B, and B a weight of 1/5 compared to A.
- The procedure then normalises these weights (there are a range of methods for this).
- Using the same general approach, there is then a pair-wise comparison of the options, one criterion at a time.
- The procedure then normalises the option comparison scores by multiplying the normalised option score by the corresponding normalised criteria weight and summing for all criteria.
- The option with the highest score is preferred.

AHP can be used for decision-making problems with both quantitative and qualitative criteria. There is no need to translate criteria onto a common scoring system as all judgements are relative (rather than absolute) between criteria, and between options.

Two further techniques[16] which support the process of option comparison are:

i) REMBRANDT – Ratio Estimation in Magnitudes or Decibels to Rate Alternatives which are non-Dominated. REMBRANDT uses a logarithmic scale instead of the 1-9 AHP scale.

ii) MACBETH – Measuring Attractiveness by a Categorical Based Evaluation Technique. MACBETH uses a six-point 'difference' scale.

5.5 Outranking

Outranking[2] is a concept which is widely deployed in Europe. The method adopts the following basic principle:

> Option *A* outranks Option *B* if, given what is understood of the decision maker's preferences, the quality of the evaluation of the options and the context of the problem, there are enough arguments to decide that *A* is at least as good as *B*, while there is no overwhelming reason to refute that statement.

Outranking uses pair-wise comparison between options. There are typically two stages of implementation of the method. In the first stage a precise way of determining whether one option outranks another is specified. At the second stage, the means by which the pair-wise outranking assessments can be combined to suggest an overall preference ranking among the options is defined. Dominance in outranking methodology uses weights to give more influence to some criteria than others:

- One option outranks another if it outperforms the other on enough criteria of sufficient importance (as reflected by the sum of the criteria weights)

  and

- is not outperformed by the other option by exhibiting inferior performance on any criteria.

All options are then assessed in terms of the extent to which they outrank all the other options. The approach effectively downgrades options that perform badly on any criterion. It can also be an effective tool for exploring how preferences between options come to be formed. The method also allows pairs of options to be categorised as ‘incomparable’.

Outranking methods seek to make fewer assumptions about the nature of the underlying process that produces preferences. It leaves more of the process of finalising choice to the decision-maker. It recognises the fact that options which record very poor relative performances on particular criteria may be hard to implement in practice.

One particular outranking method[2] is long-established: ELECTRE (*Elimination et Choix Traduisant la Réalité*). This method is available in a number of variants including ELECTRE I, II, III, IV, IS and TRI. In the simplest ELECTRE I form, the model identifies a subset of options such that any option not in the subset is outranked by at least one member of the subset. The aim is to make the subset as small as possible. This subset is then the shortlist from which the preferred option is selected. The subsequent variants develop more sophisticated approaches e.g. ELECTRE II is used to rank alternatives.

The Preference Ranking Organisation Method for Enrichment Evaluation (PROMETHEE) was introduced as an outranking method[4]. Similarly to the ELECTRE variant, there are several versions available of increasing complexity including PROMETHEE I, II and V. In the PROMETHEE method positive and negative preference ‘flows’ for each alternative are calculated. A ranking of options is obtained by analysis of these flows. A graphical representation of the PROMETHEE analysis is available in the Geometrical Analysis for Interactive Aid (GAIA) process; PROMETHEE and GAIA are used together in practice as complimentary techniques[16].

5.6 Ideal Point Methods

In the Ideal Point Method the alternatives are ranked according to their separation from an ideal point. The ideal point is defined as the most desirable, weighted, hypothetical alternative (decision outcome). The option closest to the ideal point is preferred. The separation is measured in terms of metric distance. The method employs elements of the optimisation model. One of the most popular ideal point methods is the Technique for Order Preference by Similarity to the Ideal Solution (TOPSIS)[17].

The TOPSIS method follows the following steps:

1. Obtain performance data for the alternatives over all criteria.
2. Develop a set of importance weights for each of the criteria.
3. Identify the ideal alternative (extreme performance on each criterion).

4. Identify the worst (nadir) alternative (reverse extreme performance on each criterion).
5. Develop a distance measure over each criterion to both ideal and nadir.
6. For each alternative, determine a ratio R equal to the distance to the nadir divided by the sum of the distance to the nadir and the distance to the ideal.
7. Rank order alternatives by maximising the ratio R.

5.7 'Fuzzy' Data Sets

There have been some recent applications of the use of 'fuzzy sets' in MCDA methods such as PROMETHEE[18]. Fuzzy sets allow for uncertainty in the scoring of options. For example, in the Evidential Reasoning Approach[13], instead of a single score (0-1) on a 5-point (0, 0.25, 0.5, 0.75, and 1) scale, five individual scores are applied: one to each point on the scale. Fuzzy MCDA models can also use weights that are represented as fuzzy quantities.

These methods tend to be difficult for non-specialists to understand and do not have the clear theoretical foundations of the more conventional MCDA methods. Their relatively recent introduction also means that the methods are less well established than the traditional techniques.

NAIADE (Novel Approach to Imprecise Assessment and Decision Environments; for an overview refer to[18]) uses pair-wise linguistic evaluation of alternatives. NAIADE uses fuzzy relations, based on "semantic" distance between linguistic qualifiers (e.g. "very good", "good", "moderate" etc.). NAIADE applies equal weights to all criteria.

REGIME[18] is further pair-wise comparison technique which allows for uncertainty in scoring and weighting.

6 Other Tools And Techniques

As previously discussed, (see for example[5]), there are a wide range of MCDA decision-making tools and methodologies in existence. In addition, there are a number of approaches which are used in supporting MCDA. Many of these techniques are prominent in their own right in related fields. In this review we will very briefly describe:

- The financial analysis tools Cost-Benefit Analysis (CBA) and Cost-Effectiveness Analysis (CEA)
- Life Cycle Analysis/Assessment (LCA)
- Geographic Information Systems (GIS)

6.1 Financial Analysis

6.1.1 CBA

Cost-Benefit Analysis is a financial analysis tool for weighing up the benefits of an investment against its costs. All positive and negative impacts are expressed in monetary terms. Benefits are measured by the maximum amount of money that recipients would pay for them, and detriments by the minimum amount of money that recipients would accept as compensation for them.

CBA is an example of a single criterion approach. CBA is in widespread use, sometimes in conjunction with use of MCDA for those costs and benefits for which monetary valuation is not achievable. Nonetheless application is constrained by:

- The difficulty of expressing all impacts, particularly environmental ones, in monetary terms on a consistent basis.
- Uncertainties over the appropriate discount rate to apply to future costs representing health and environmental effects

6.1.2 CEA

Cost-Effectiveness Analysis (CEA) is a simplified form of CBA in that it aims to derive the lowest cost option which meets a stated objective. The benefits of the option in meeting the objective do not need to be expressed in monetary terms.

6.2 LCA

Life Cycle Analysis (or Assessment) is a technique for assessing the potential environmental aspects of a product or service. This is achieved through:

- Compilation of an inventory of process inputs and outputs.
- Evaluation of the environmental aspects associated with the above inputs and outputs.
- Assessment of the aspects in relation to the objectives of the LCA scope.

6.3 GIS

Geographic Information Systems are used to display information on a geographic basis. A GIS database is created to store the data associated with different options along with the background information and map for the locality. Information from the assessment of options can be displayed geographically, either individually or for pairs/groups of options at a time.

Powerful GIS tools have been developed and are in widespread use, particularly for screening options e.g. for Strategic Environmental Assessment (SEA) studies. GIS systems can be expensive to maintain and their heavy use of data can make the process unwieldy in practice for the decision maker(s).

7 Summary

In this section the main MCDA methodology groupings are described and compared in terms of inherent key strengths and weaknesses. It can be seen from the table below that there are a number of considerations when selecting the most appropriate method, or combination of methods.

Method	Description	Strengths	Weaknesses
Non-Compensatory 'Elementary' Methods	Range of methods which compare options against a common set of criteria without allowing any compensation between criteria i.e. strong vs. weak.	Uses elementary techniques so can be implemented rapidly.	Lack of compensation restricts application to simple cases.
Linear Additive	Option value scores are multiplied by the criteria weights and the weighted scores added.	Well established. Robust and effective on wide range of problems.	Uncertainty not formally built in (but can be appended). Variety of circumstances in which decision support is required has led to development of more sophisticated models.
Multi-Attribute Utility Theory (MAUT)	Expression of overall performance of an option in terms of a single non-monetary number representing the utility of that option. Criteria weights are often obtained by directly surveying stakeholders.	Easier to compare options whose overall scores are expressed as single utility numbers. Choice of an option can be transparent if highest scoring option is chosen. Based on utilitarian philosophy. Many people prefer to express net utility in non-monetary terms.	Maximisation of utility may not be important to decision makers. Criteria weights obtained through less rigorous stakeholder surveys may not accurately reflect true stakeholder preference. Rigorous stakeholder preference elicitations can be expensive.
Analytical Hierarchy Process (AHP)	Criteria weights and scores are based on pair-wise comparisons of criteria and options, respectively.	Pair-wise comparison is easier for the decision-maker(s) to undertake than comparing many options simultaneously.	The weights obtained from pair-wise comparisons may not truly reflect people's true preferences. Mathematical procedures used to generate summary scores can sometimes produce illogical results.

Method	Description	Strengths	Weaknesses
Outranking	One option outranks another if it out-performs the other on enough criteria of sufficient importance as reflected by the sum of criteria weights) and is not outperformed by the other in the sense of recording a significantly inferior performance on any one criterion. Allows options to be classified as incomparable.	Does not require the reduction of all criteria to a single unit. Explicit consideration of the possibility that very poor performance on a single criterion may eliminate an option from consideration even if that criterion's performance is compensated for by very good performance on other criteria.	Does not always take into account whether over-performance on one criterion can make up for under performance on another. The algorithms used in outranking can be relatively complex and may not be well understood by decision makers.
Ideal Point	Options are ranked according to their separation from ideal and nadir points.	Identifies best option quickly.	Relatively new method; not in widespread use.

Table 1 Comparison of MCDA Methods

8 Conclusions

This report provides a summary of MCDA techniques. Subsequent reports will identify appropriate criteria against which options will be assessed and recommend the MCDA technique(s) that are most appropriate for use in the CARBOWASTE project.

It order to constrain the size of the report, the present report draws upon a number previous reviews of decision-making tools and techniques. Several of these have been carried out at national and European levels. The report then describes the MCDA tools and techniques that are prominent in use and in the literature, starting with the most basic 'elementary' techniques and progressing to the more sophisticated and flexible methods.

The inherent strengths and weaknesses of the main methods are discussed. There are a range of techniques which are suitable for deployment on the CARBOWASTE project, depending on the precise application, and these will be considered further in the next phase of work.

9 References

1. Carbowaste: Treatment and Disposal of Irradiated Graphite and Other Carbonaceous Waste, February 2008, 7th Framework Euratom Nuclear Research and Training Activities, Grant Agreement 211333, Annex 1 Version U, European Commission
2. Multi-Criteria Analysis Manual, Department for Transport, Local Government and the Regions, 2001, UK; available from the Communities and Local Government Department
3. Baker D., Bridges D., Hunter R., Johnson G., Krupa J. Murphy J., Sorenson K., December 2001, Guidebook to Decision-Making Methods, U.S. Department of Energy, WRSC-IM-2002-00002
4. Linkov I., Varghese A., Jamil S., Seager T.P., Kiker G., Bridges T., Multi-Criteria Decision Analysis: A Framework for Structuring Remedial Decisions at Contaminated Sites, in Linkov I. and Ramadan A, Eds, “Comparative Risk Assessment and Environmental Decision Making”, Kluwer 2004 p15 -54
5. Building Environmental Assessment Consensus, The SEA Manual, Fact Sheets, A Sourcebook on Strategic Environmental Assessment of Transport Infrastructure Plans and Programmes, October 2005, European Commission, DG TREN
6. Bardos P., Lewis A., Nortcliff S., Matiotti C., Marot F., Sullivan T., Review of Decision Support Tools for Contaminated Land Management, and their Use in Europe, A report from the Contaminated Land Rehabilitation Network for Environmental Technologies (CLARINET), November 2002, European Commission
7. European Commission Nuclear Science And Technology Cooperative Research on the Governance of Radioactive Waste Management (COWAM-2), Contract No FI6W-CT2003-508856, Final Report, Directorate-General for Research, 2008, Euratom, EUR 23186
8. Fifth Framework Programme Development And Application Of A Multi-Criteria Decision Analysis Software Tool For Renewable Energy Sources (MCDA-RES), Contract NNE5-2001-273, Final Reports (1-20), 2004, European Commission
9. DAC Guidelines and Reference Series, Applying Strategic Environmental Assessment, Good Practice Guidance For Development Co-Operation, 2006, OECD, ISBN: 92-64-02657-6
10. Guidelines for Applying Multi-Criteria Analysis to the Assessment of Criteria and Indicators, the Criteria and Indicators Toolbox Series No. 9, 1999, CIFOR, ISBN: 979-8764-27-7
11. Turner S., Multi-Attribute Decision Analysis in the U.K. Nuclear Industry, Pub. 10 August 2007 in Issue 49 of The Environmentalist
12. Committee on Radioactive Waste Management, Managing our Radioactive Waste Safely, CoRWM’s Recommendations to Government, July 2006, CoRWM Document 700
13. Xu D., Yang J., Carlé B., Hardeman F., Ruan D.- Application of intelligent decision system to nuclear waste depository option analysis.- in Applied Artificial Intelligence, Proceedings of the 7th International FLINS Conference, Genova, Italy, 29-31 August 2006, Genova, Italy, Flins, 2006, p. 867-874

14. Greneche D., Quiniou B., Boucher L., Delpech M., Gonzalez E., Alvarez F., A.Cuñado M., Wallenius J., Westlén D., Zimmerman C., Marivoet J., Eds. Nabbi R., Odoj R., Rossbach M., von Lensa W., Red Impact: Impact of Partitioning, Transmutation and Waste Reduction Technologies on the Final Nuclear Waste Disposal, Synthesis Report, September 2007, European Commission FP6 Contract No. FI6W-CT-2004-002408
15. V. Belton, T.J. Stewart, Multiple Criteria Decision Analysis: An Integrated Approach, 2002, Kluwer Academic Publishing, Boston, ISBN 79237505X
16. Figueira J., Greco S., Ehrgott M., Multiple Criteria Decision Analysis: State of the Art Surveys, 2005, Springer, ISBN 038723067X
17. Olson D.L., Comparison of Weights in TOPSIS Models, May 2004, Mathematics and Computer Modelling 0 (2004) 1-0, Pergamon, Elsevier Science Ltd.
18. Stagl S., SDRN Rapid Research and Evidence Review on Emerging Methods for Sustainability Valuation and Appraisal, a report to the Sustainable Development Research Network, Final Report, January 2007, Sustainable Development Research Network