Multi-Criteria Analysis for Assessing Sustainability of Remedial Actions

Applications in Contaminated Land Development

A Literature Review

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SUMMARY

A large number of the contaminated sites in Sweden are located in the urban city environment, and soil and water remediation is often necessary when these areas are exploited. Construction companies typically facing complex challenges when buying former contaminated land for exploitation purposes, e.g. project risks such as delays associated with remediation, legal concerns or communication issues. The situation with a contaminated site results in a need to reduce the potential risk for human health and/or the environment through remedial measures. Remediation efforts have traditionally been viewed as a sustainable action. However, during the last few years a discussion has emerged where this is being questioned since remedial activities may themselves cause negative impacts, e.g. emissions, energy use, transport risks, risk of injury at the remediation site and acute contamination risks during remediation. There is no single framework or assessment method that takes a holistic view, a view on sustainability, of remedial actions. There is hence a demand for a method which allows for consideration of the sustainability of remedial actions and risk management including both local and global effects as well as project risks associated to remediation in construction projects. The assessment method should also support stakeholder involvement in a robust and transparent way. Such methods can be based on e.g. Multi-Criteria Analysis (MCA) or Multi-Criteria Decision Analysis (MCDA) (e.g. Vegter et al., 2002, Bardos, 2003), Cost-Benefit Analysis (CBA), Cost-Effectiveness Analysis (CEA) and Life-Cycle Analysis (LCA) (Bardos, 2003). This literature review is a part of a method development, based on MCDA, for sustainability assessment of remedial actions in construction projects. In this literature review, an overview on sustainable development and sustainable remediation, environmental protection and remediation in Sweden is presented and effort is put on describing how remediation is connected to construction projects. A review of criteria used in MCDA applications is presented and a special effort is directed to an introduction to the theory of MCDA methods and an overview of the use of MCDA in remediation projects and adjacent areas e.g. decisions on waste disposal sites and after use plans for urban quarries. The most important conclusions of this literature review are: sustainability of remedial actions is in great focus among remediation experts but no single accepted framework or method is available for assessment. MCDA is viable for assessments and have been used previously for these purposes. It is of great importance to encourage stakeholder involvement in the process of conducting MCDA in remediation projects and important to take uncertainties into account.

Key words: Multi-Criteria Analysis, Sustainable remediation, Decision Support Tools, Construction projects, Remediation

Contents

Preface

This literature review has been carried out at the Department of Civil Engineering, Division of GeoEngineering at Chalmers University of Technology in Sweden. Professor Lars Rosén, Assistant Professor Jenny Norrman and Technical Doctor Malin Norin have supervised the work. The literature review is a part of a PhD project funded by the Development Fund of Swedish Construction Industry (SBUF) and NCC AB.

Göteborg, October 2011

Petra Brinkhoff

1 Introduction

This literature study is a part of a research effort which aims at developing an assessment tool for sustainability assessment of remediation prior to development on contaminated land. The assessment is planned to be performed through an Multi-Criteria Decision Analysis (MCDA) and the result will be a Decision Support Tool (DST) mainly intended for use by construction companies. The contaminated sites in focus of remedial actions are e.g. former industrial sites in urban areas planned to be redeveloped by construction companies.

For the purpose of developing an MCDA model for evaluating remediation alternatives prior to construction, selecting its criteria, as well as building a relevant criteria hierarchy, an inventory of applications of MCDA in national and international projects have been conducted. The criteria can be seen as sub-objectives of the overall objective which in this case is an evaluation of the sustainability of remediation alternatives. It is against these criteria which the effects of the remediation alternatives are assessed.

1.1 Background

There are approximately 80 000 contaminated sites in Sweden (SEPA, 2009) with a potential risk for human health and/or the environment. This situation results in a need for remediation measures. According to the Swedish Parliament (SR, 2010), the average cost for remediation of a heavily contaminated site is around 40 million Swedish kronor. A large number of the contaminated sites are located in the urban city environment and the soil and water remediation is often performed when urban areas are exploited. Construction companies are one of the involved parties in such exploitation. They face complex challenges when buying former contaminated land for exploitation purposes, e.g. project risks such as delays associated with remediation, legal concerns or communication issues.

Remediation efforts have traditionally been viewed as a sustainable action. However, during the last few years a discussion has emerged where this is being questioned since remedial activities may themselves cause negative impacts (Vegter et al., 2002). Examples of such negative impacts are emissions, energy use, transport risks, risk of injury at the remediation site, acute contamination risks during remediation and long term environmental risks at the disposal site.

The remediation technique most often used in Sweden is according to Helldén et al. (2006) excavation combined with disposal, often referred to as “dig and dump”. There are several reasons why “dig and dump” has been so widely used, e.g. relatively low disposal costs and a wish for quick measures to reach acceptable risk levels. A wish for quick measures is often the reason during a redevelopment. Further, there has been a limited concern about the negative effects of excavation and disposal, e.g. high impact of emissions during truck or boat transports, worker safety and long term environmental effects at disposal sites.

However, even though excavation is necessary at times, due to technical circumstances, there is a need for assessing the impacts of excavation and other remedial alternatives. The Swedish Environmental Protection Agency (SEPA) requires that remediation projects consider the sustainability of different remediation alternatives during the remediation alternative selection process within the risk evaluation.

There is hence a demand for assessment methods, Decision Support Tools (DSTs), which allows for consideration of sustainable development and risk management in a mutual and holistic way and support stakeholder involvement in a robust and transparent way. Such methods can be based on e.g. Multi-Criteria Analysis (MCA) or MCDA (e.g. Vegter et al., 2002, Bardos, 2003), Cost-Benefit Analysis (CBA), Cost-Effectiveness Analysis (CEA) and Life-Cycle Analysis (LCA) can be parts of such DSTs (Bardos, 2003).

Sustainable remediation build on the concept of sustainable development outlined by the Bruntland commission`s report: *"Our common future"* (WCED, 1987). Sustainable development implies a development where the economic dimension, the ecologic and socio cultural dimensions are equally important and interact with each other.

1.2 Scope and Objectives

The aim of this literature study is seven-folded: (1) to give a general description of the MCA/MCDA procedure, (2) to present a broad overview of the available literature regarding MCA/MCDA as an assessment tool to compare remediation alternatives, (3) to briefly describe the criteria inventory process (4) to give a general description of different remediation techniques, (5) to highlight in what stages of the building process environmental land issues and project risks exists, (6) to give an overview of the legislative framework for remediation of contaminated land and (7) to describe the SEPAs view on choosing remediation alternative.

1.3 Structure of the report and limitations

The international sustainability perspective and views on sustainable remediation are briefly introduced in *Chapter 2*. *Chapter 3* includes the 16 Swedish environmental objectives, a description of the Swedish Environmental Code, what parties that take an active role in a remediation project, SEPAs starting points of remediation as well as and an overview on SEPAs guidance on choosing remediation alternative. *Chapter 4* handles construction companies and their connections to remediation; the building process, environmental issues, project risks and what legal aspects construction companies face prior to building on contaminated land. *Chapter 5* reviews remediation strategies and technologies and *Chapter 6* is about MCA and MCDA methodology. CBA and CEA are briefly described in this chapter. Several Swedish and International examples of MCDA methods used when working with remediation of contaminated sites are reviewed in *Chapter 7*. *Chapter 8* gives an overview of some Decision Support Tools (DSTs) available on the market focusing on sustainability appraisals. This chapter also state other applications of MCDA than in remediation projects. *Chapter 9* contains a discussion and conclusions of this literature study.

There are limitations made in the section of remediation techniques (Chapter 5). Only the most common and widely used techniques have been described.

2 Sustainable development

2.1 Concept of sustainable development

The idea of sustainable development started to take form on the global arena at the 1972 UN Conference on Human Environment. There was an agreement between 113 countries at the conference about cleaning up the environment and starting to address environmental issues on a global scale. The agenda turned to antigrowth since environmentalists saw that consumption of natural resources was intimately linked to economic development. This was not liked by the Third world which saw the new agenda as yet another way of stopping development of the Third World (Newman and Kenworthy, 1999).

As a response to this disagreement, the UN established the World Commission on Environment and Development in 1983. This was an attempt to resolve the fundamental conflict between the first and the third world. The commission's work resulted in a report: *Our Common Future* (Bruntland report) published in 1987 (WCED, 1987). The phrase sustainable development has after the report was published been used when speaking in colloquial language. At the 1992 Earth Summit in Rio de Janeiro the environment was placed at a global economic agenda compared to the 1972 UN Conference when it was placed on the global political agenda (Newman and Kenworthy, 1999).

Four principles are derived from the Bruntland report by Newman and Kenworthy (1999). These principles are fundamental approaches to global sustainable development. It is a requirement that they are applied simultaneously for any approach. The four principles are:

1. *Elimination of poverty, especially in the Third World. This is necessary not just on human grounds but as an environmental issue.* Rapidly growing populations are dependent on agriculture, plant collection and fishing and if no economic and social development occurs at the same time it will lead to stress on the environment.
2. *The First World must reduce its consumption of resources and production of wastes.* The inequity of resource consumption existing in the world cannot continue if a sustainable development is to take place. A member of the First World consumes 500 times more natural resources than a very poor member of the Third World. An economic and social change is necessary to achieve sustainable development in the future. New technology using less energy, switching to new renewable fuels and more efficient materials are progress towards a more sustainable society.
3. *Global cooperation on environmental issues is no longer a soft option.* It is very important and essential for success that all nations and their leaders work together to deal with the environmental problems like Green-House Gases, ChloroFluoroCarbon compounds and hazardous wastes. It is globalism that is the precursor to understanding sustainability.
4. *Change toward sustainability can occur only with community-based approaches that take local cultures seriously.* The changes discussed can only occur when local communities decide how to solve their own economic and

environmental conflicts. The solution involves a simultaneous improvement of both. A development of local cultures and communities is the precursor to implementing sustainability(Newman and Kenworthy, 1999).

In the summary of the Bruntland report the commission states that the growing environmental problems are linked to the South´s enormous poverty and the North´s unsustainable consumption and production. The following citation from the report: "**development that meets the needs of the present without compromising the ability of future generations to meet their own needs**" is famous and outlines a strategy how to think about sustainable development (Kemp and Martens, 2007).

Even though there are more than a hundred definitions on sustainable development, the essence is the same; sustainable development is to supply for the fundamental human needs of man in an equal way while trying not to violate the nature on Earth (Kemp and Martens, 2007).

Figure 2-1 (Beatley, 1994) shows the ethical approaches illustrated in a coordinate system, ranging from utilitarian to duty-based on the y-axes and from anthropocentric to non-anthropocentric on the x-axes. The concept sustainable development is an ethical approach which can be classified as duty-based and anthropocentric (Bardos, 2009). Bardos (2009) stress that there are concepts of sustainable development that is more eco-centric, than the view put forward in the Bruntland report, e.g. maintenance of ecosystem services. For further reading about the importance of eco-system services see e.g. Costanza et al., 1997, de Groot et al., 2002, Boyd and Banzhaf, 2007.

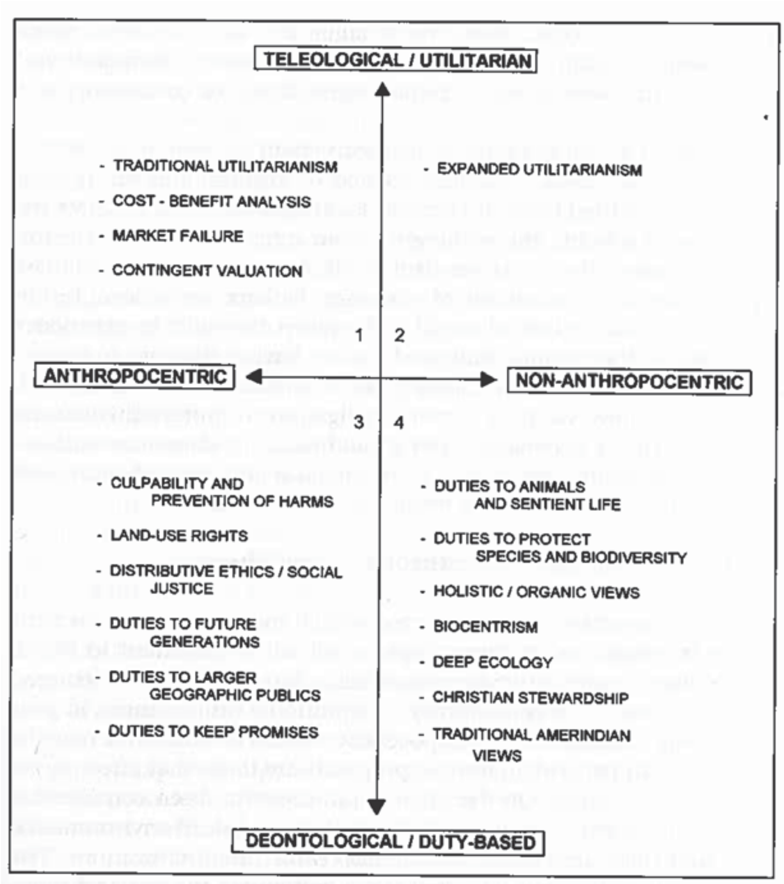


Figure 2-1. Classification of ethical approaches, from Beatley (1994).

After publication of the Bruntland report many attempts have been made to operationalize sustainable development and the most famous is the three pillar concept also called P3. P3 represents Planet, People and Profit and is either visualized by the pillar structure, overlapping circles or concentric circles (Adams, 2006) for the last two see Figure 2-2. The circles illustrate the environment, the society and the economy. When these aspects are interacting, sustainable development can be achieved (Kemp and Martens, 2007).

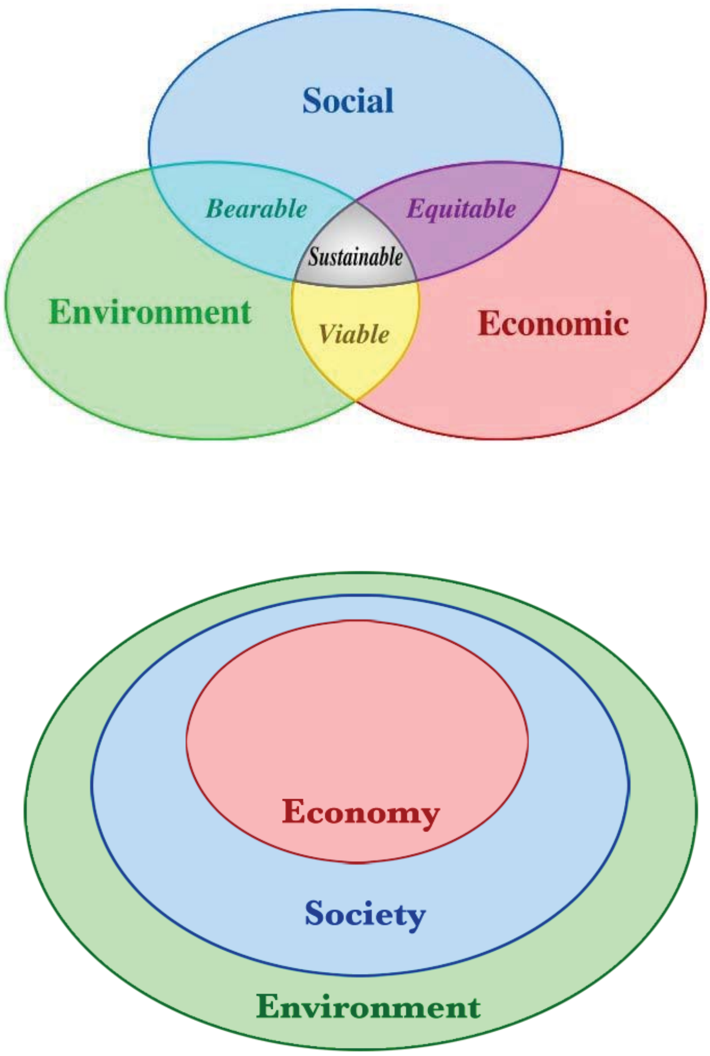


Figure 2-2: The three interacting dimensions in sustainable development, the environment, the social and the economic dimension visually presented in two different ways (Figures from Adams, 2006, Söderqvist et al., 2004).

The "sustainable development" perspective differs from "sustainability" in its favour of growth. It is argued that the growth in sustainable development should be a different kind of growth but still growth is important. The term "sustainability" is often preferred by people favouring value change and life style change (Kemp and Martens, 2007).

Bleicher et al. (2010) state that sustainable development has to be understood as dependent on space, time, scale and actors involved. Any understanding about sustainability or sustainable development has to be context-sensitive.

Sustainability science is a growing field of research. This is a trans-disciplinary field where work in economic, social and development studies are combined to better understand the complex dynamic interactions between environment, society and economy (Kasemir, 2003).

The goals of sustainable development need to be assessed to show whether a transition towards sustainability is taking place. As a consequence of the need to assess sustainability, sustainability tools are developed. Ness et al. (2007) present a framework for sustainability assessment tools where they categorize the available tools. The framework has a temporal focus along with the object of focus for the tool. The monetary valuation, see the bottom of Figure 2-3, can be used at any time. The boxes with thick lines are tools that enable an integrated assessment of nature-society systems into a single evaluation (Ness et al., 2007).

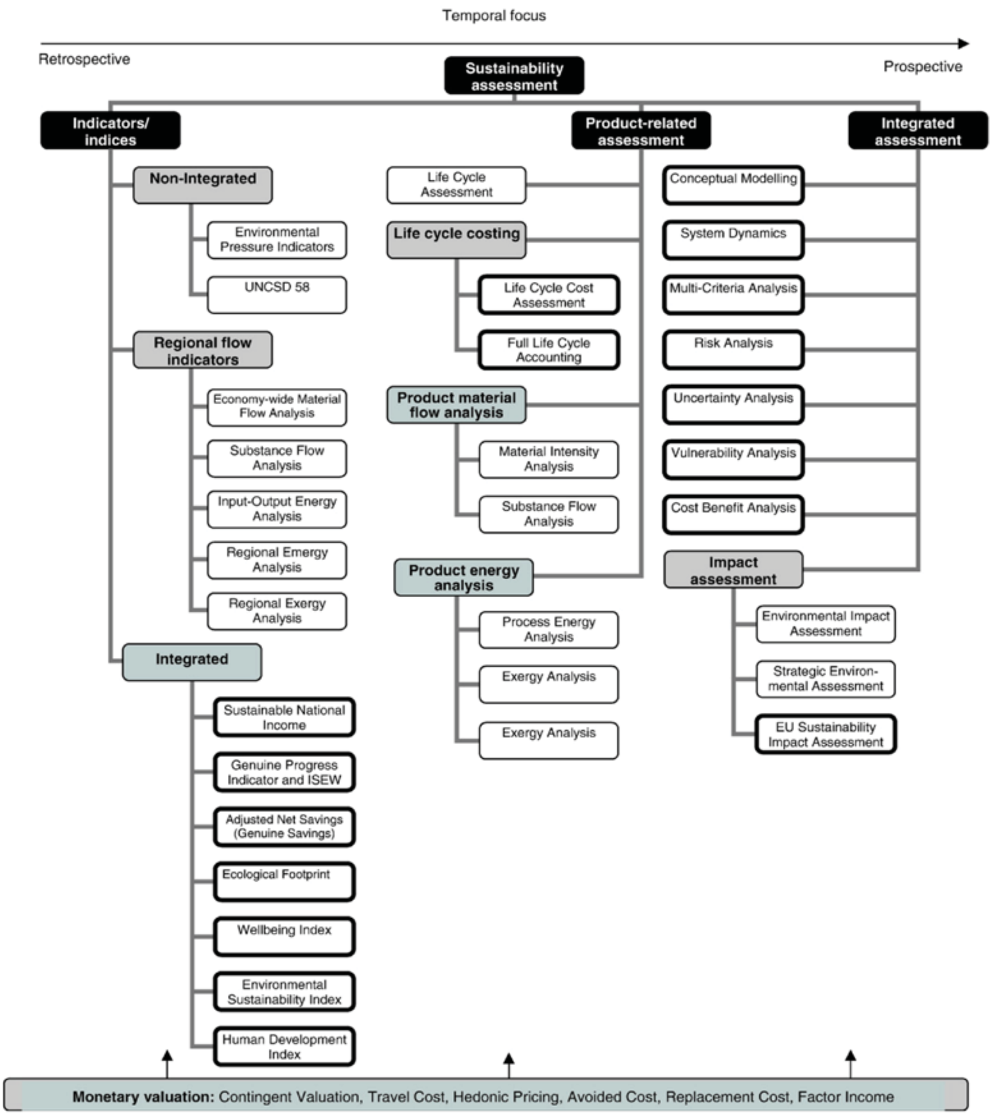


Figure 2-3. Framework for sustainability assessment tools, from Ness et al. (2007).

Therivel (2004) have researched metrics, models and tools for describing, predicting and evaluating behaviour towards sustainability. The author also give a thorough description and analysis of available sustainability assessment tools (Therivel, 2004).

2.2 Sustainable remediation

Sustainable development in contaminated land management (CLM) and more specifically sustainable remediation is a growing field of knowledge. At a strategic level, remediation of contaminated sites supports the goal of sustainable development through:

- the act of conserving land as a resource
- prevent spreading of pollutants to the air, the soil and the water
- reducing the pressure on development on Greenfields

Although all these positive effects occur due to remediation some negative effects also arise: on the environment, economy and society. These negative impacts should not exceed the benefits of a remediation (Bardos et al., 2002).

In the CLARINET report *Sustainable management of contaminated land* (Vegter et al., 2002) it is stated that the development of integrated and sustainable approaches has shifted focus from assessment of problems towards a focus on solutions that will meet both present and future needs of society.

There are no united guidelines or common methodology for sustainable remediation assessments used by all nations in EU or internationally. According to Woodward et al. (2009), this is a possible barrier for implementing sustainable remediation. Another possible barrier is the difficulty to equate results in a consistent metric since many of the factors influencing the outcome needs a qualitative assessment.

There is a variety of views and no uniform picture of what sustainable remediation is and how it should be assessed. Lesage and Zoller (2001) have the following view on sustainable remediation.

> "Sustainable remediation is developing methods that do not require extraordinary resources, or resources better used elsewhere. It is working with nature, by using supporting natural processes technologies, rather than against it. It is achieving balance between risk mitigation and the expenditures required to achieve it, through optimization based on well-defined criteria" (Lesage and Zoller, 2001).

Internationally, USA has been working with issues of sustainability frameworks, e.g. the first Sustainable Remediation Forum (SuRF) initiative (http://www.sustainableremediation.org/) and the initiative of green remediation by United States Environmental Protection Agency (USEPA)

The definition of Green Remediation is, according to USEPA (2008) "the practice of considering all environmental effects of remedy implementation and incorporating options to maximise net environmental benefits of clean-up actions". Green remediation reduces the demand on the environment during remediation, also known as the footprint of remediation. The potential footprint encompasses impacts e.g.

- Air pollution caused by toxic
- Water cycle imbalance
- Soil erosion and nutrient depletion
- Ecological diversity and population reduction
- Emissions of Green House Gases (GHG)

Green remediation differs to sustainable remediation since it tries to select the most environmentally-friendly technology, focusing on energy use, to achieve a given remedial objective (Smith et al., 2010). Sustainable Remediation Forum for UK (SuRF–UK) considers remediation as being a part of broader sustainable development objectives of the project and not only to select the most "environmental-friendly" technology.

Woodward et al. (2009) states that even though the authors do not want to advocate sustainable remediation over green remediation there are demands that need be addressed besides climate change and diminishing natural resources. These are off-site impact which should not only include the nearest receptors but the greater environment and the society as a whole. For a Sustainable remediation it might also be appropriate to add a LCA and a CBA in the selection process (Woodward et al., 2009).

Work on forming frameworks in the area of sustainable remediation is in progress. In Europe, the Contaminated Land Applications In Real Environments (CLAIRE) has published a document within SuRF-UK (Smith et al., 2010). The document is an attempt to form a framework for assessing the sustainability of soil and groundwater remediation. Other institutions working with these questions are NICOLE (Network of Industrially Contaminated Sites in Europe) and the former Contaminated Land Rehabilitation Network For Environmental Technologies in Europe (CLARINET).

SuRF-UK recommends a tiered approach, qualitative and quantitative assessment, to assess sustainable remediation and stress that the specific tool used is not that important but the process and thought behind the assessment is. SuRF- UK lists a number of decision support techniques with relevance to sustainable remediation assessments. These all seek to assess the environmental, social and economic benefits and costs for remediation alternatives that meet a project goal, see Table 2-1 (Smith et al., 2010).

The techniques, from Table 2-1, which are able to handle both quantitatively and qualitatively data and have a flexible coverage in the different elements of sustainable development i.e. the economic, environmental and social categories, are scoring/ranking systems such as MCA and CEA. MCA is also highlighted by Ness et al. (2007) as a tool which enables an integrated assessment of nature-society systems into a single evaluation, fig 2-3.

Technique	Environment	Economy	Society	Type	CLM Application?
Scoring / ranking systems (including multi-criteria analysis)	Narrow to Wide	Narrow to Wide	Narrow to Wide	Both	Yes
Best Available Technique (BAT)	Narrow to Wide	Narrow	-	Qual	Yes
Carbon footprint ("area")	Narrow	-	-	Quan	Yes
Carbon balance (flows)	Narrow	-	-	Quan	-
Cost benefit analysis	Narrow to Wide	Narrow to Wide	Narrow to Wide	Quan	Yes
Cost effectiveness analysis	Narrow to Wide	Narrow to Wide	Narrow to Wide	Both	Yes
Eco-efficiency	Narrow	-	-	Quan	-
Ecological footprint	Narrow	-	-	Quan	-
Energy / intensity efficiency	Narrow	-	-	Quan	Yes
Environmental risk assessment	Narrow to Wide	-	-	Both	Yes
Human health risk assessment	-	-	Narrow	Both	Yes
Environmental impact assessment / Strategic environmental assessment	Narrow to Wide	-	-	Qual	Yes
Financial risk assessment	-	Narrow	-	Quan	Yes
Industrial ecology	Narrow to Wide	Narrow to Wide	-	Quan	-
Life Cycle Assessment (based)	Narrow to Wide	-	-	Quan	Yes
Quality of life assessment	Wide	Wide	Wide	Qual	-

Notes:
Qual = Qualitative
Quan = Quantitative
Both = Qualitative and/or quantitative
CLM = Contaminated Land Management
- = Technique has no known coverage

Table 2-1. Decision support techniques with relevance to sustainable remediation assessment, from Smith et al. (2010).

The assessment of remediation is typically based on an assessment of the performance of different alternatives against a list of indicators or criteria (see Box 1 in section 6.1.3 for a terminology discussion). For the assessment of soil and groundwater, SURF-UK has developed a set of sustainability indicators. These are divided in three overarching elements; environmental, social and economic, i.e. the elements of sustainable development. Further, 18 categories, six in each element, have been found to be relevant for sustainability assessment. These sustainable remediation indicators including explanations can be found in Appendix 1.

2.3 Summary of criteria from international and Swedish projects

For the purpose of constructing a hierarchy of criteria, as a part of the MCDA model development in the research effort which this literature study is a part of, a search in international papers, decision support software and reports has been conducted. The search was intent on finding literature that contained criteria, considered important in decision-making concerning sustainable remediation of contaminated land. This literature was found through searches in the databases SCOPUS and CSA Illumina which are multidisciplinary databases.

The search for literature included search strings as “sustainable remediation”, sustainable remediation and contaminated land and sustainability criteria and remediation or contaminated land. Literature where MCDA methods had been used for assessing impacts of, as well as selecting, remediation alternatives was also included in the search. Examples of such search strings are: MCA or MCDA and “sustainable remediation” and MCA or MCDA and contamination or land remediation.

The search resulted in a list of inventory criteria. The list contains 364 criteria from 30 sources. The inventory criteria have further been categorised according to the three elements of sustainable development; ecology, economy and socio-culture, see Appendix 2. The references used for compiling the inventory list are given in Appendix 2 as well.

A continuation of this categorisation will be performed in the near future, where the inventory criteria will be further categorised according to Rosén et al’s (2009) sub-criteria. After this categorisation the inventory criteria will be grouped according to resemblance and second level sub-criteria, to be used in the MCDA model, will be derived. This work will be described further in coming publication.

3 Environmental protection and remediation in Sweden

3.1 Swedish Environmental Objectives

The Swedish environmental objectives are according to the Swedish Protection Agency (SEPA) leading the way to a sustainable society (SEPA, 2009). The Swedish parliament has established 16 objectives for the environmental quality, Table 3-1. The objectives describe the quality and state of the Swedish environment, nature and cultural resources. The goals are to be reached in one generation (except for the climate goal). The aims of the environmental quality objectives are:

- Promote human health
- Protect biodiversity and the natural environment
- Ensure the cultural and natural environment
- Save the ecosystems long-term capacity for production
- Secure a healthy consumption of natural resources

The Swedish parliament adopted 72 sub-goals in November 2005, to concretize the environmental efforts towards the environmental goals. In June 2009, the parliament decided on further sub-goals for the objective *reduced climate impact*. These sub-goals puts focus and perspective on the “problem” in question either as a part of the overall quality objective or as a step on the way. There are three major environmental issues attended, in addition to the 16 environmental quality objectives. These three are targeted on the (1) *cultural environment, (2) health* and *physical planning* and *(3) management of land and water and buildings* (Miljömål, 2009).

The parliament has decided that work with environmental quality objectives will concentrate on three intervention strategies: *efficient energy use and transport, non-toxic and low-input circuit* and *management of land, water and the built environment.* These strategies are pin-pointed since a handful of activities cause impacts on several environmental issues such as transportation, energy use, material flow and the use of chemicals. Specific measures in these areas can result in an achievement of several environmental quality goals at the same time (Miljömål, 2009).

Table 3-1 show the environmental objectives and the definitions. The most important environmental objectives regarding contaminated land issues are indicated with a star. The objective *non-toxic environment*, (no. 4), has sub objectives on remediation of contaminated sites. Sub objective 6 states that: all contaminated sites posing an acute risk of direct exposure and contaminated sites which today, or in the near future, threaten important water sources or valuable natural areas should be investigated and if necessary, remediated at the end of 2010. Sub objective 7 states that: measures have to be performed to such an extent, in areas of priority, between the years 2005 and 2010 to enable the contamination problem, in its entirety, to be largely resolved at the latest by 2050 (SEPA, 2008). It is predicted that it should be possible to reach sub goal 6 within the time limit. The prediction about sub goal 7 is that it is not possible to reach in regard to the 2010 time limit, but probably with regard to the 2050 time limit (SEPA, 2010).

Table 3-1. The 16 Swedish environmental objectives including definitions. Most important objectives for contaminated land are indicated with a star (Nilsson and Hellberg, 2009).

1* Reduced Climate Impact: A stabilization of concentrations of GHG at levels which ensures that human interference with the climate system does not become dangerous **3.1.1.1** The goal will be achieved in such a manner and at such a pace that biodiversity conservation, food production and ensuring sustainable development objectives are not compromised.
2 * Clean Air: The air must be clean enough that human health and animals, plants and cultural values are not put to risk.
3 Natural Acidification Only: The effects of acidic deposition and land use must be below the limits that can be tolerated by soil and water. The deposition of acidifying substances must not increase the rate of corrosion of technical material or cultural artefacts and buildings.
4 * A Non-Toxic Environment: The environment must be free of man-made or extracted compounds and metals which could threaten human health or biodiversity.
5 A Protective Ozone Layer: The ozone layer must be replenished to ensure a long-term protection against harmful UV radiation.
6 A Safe Radiation Environment: Human health and biodiversity must be protected against harmful effects of radiation in the external environment.
7 Zero Eutrophication: Nutrient levels in soil and water must not be such that they have any negative impact on human health, the conditions for biodiversity or the potential of varied use of land and water
8* Flourishing Lakes and Streams: Lakes and rivers must be ecologically sustainable and their diverse habitats must be preserved. Natural productive capacity, biodiversity, cultural heritage and the ecological and water-conserving function must be preserved, while the conditions for recreational activities are protected.
9 * Good-Quality Groundwater: Groundwater must provide a secure and sustainable supply of drinking water and contribute to a viable habitat for plants and animals in lakes and streams
10* A Balanced Marine Environment, Flourishing Coastal Areas and Archipelagos: The North Sea and the Baltic Sea must have a sustainable productive capacity and biodiversity must be preserved. Coasts and archipelagos must have a high degree of biodiversity, **3.1.1.2** recreational value as well as natural and cultural assets. Industries, recreation and other utilization of the seas, coasts and archipelagos must be compatible with the promotion of sustainable development. Particularly valuable areas must be protected from encroachment and other disturbance
11* Thriving Wetlands: The ecological and water-conserving function of wetlands must be maintained and valuable wetlands preserved for the future.
12* Sustainable Forests: The value of forests and forest land for biological production must be protected, at the same time as the biological diversity and cultural values and social values are protected.
13 A Varied Agricultural Landscape: Farmed landscape and agricultural land value for biological production and food production must be protected, at the same time as the biodiversity and cultural values are preserved and strengthened.
14 A Magnificent Mountain Landscape: The pristine value of mountain environments must be largely preserved in terms of biodiversity, recreational value and natural and cultural values. Activities in the mountain areas must respect these values with a view of promoting sustainable development. Particularly valuable areas must be protected from encroachment and other disturbance.
15* A Good Built Environment: Cities, towns and other built environment should be a good healthy living environment and contribute to good regional and global environment. Natural and cultural assets must be protected and developed. Buildings and facilities must be located and designed according to environmentally sound principles and in such way promote sustainable management of land, water and other resources.
16*A Rich Diversity of Plant and Animal Life: Biodiversity must be preserved and used sustainably, for benefit of present and future generations. Species habitats and ecosystems and their functions and processes must be safeguarded. Species is to survive in the long-term viable populations with sufficient genetic variation. Finally, people must have access to good quality natural and cultural environment with rich biodiversity, as the basis for health, welfare and quality of life and well-being.

3.2 The Swedish Environmental Code

The Environmental Code is the legislative framework for environmental issues in Sweden and accordingly, contaminated sites are mainly regulated by this. The Code came into force on January 1st 1999 to coordinate, broaden and strengthen the environmental law for a sustainable development. It merged the rules from sixteen different previous environmental laws.

The single, overarching purpose of the Environmental Code and environmental quality objectives is to promote ecologically sustainable development. The environmental quality objectives reflect the political will to perform environmental work, while the Environmental Code is a management tool among other things intended to achieve the goals. All provisions of the Environmental Code are to be applied so that the aim and objectives of the code is best met. In case of doubt about what should be agreed upon or performed, the environmental objectives are guiding. The objective most likely to benefit sustainable development is chosen (Miljömål, 2009).

The tenth chapter of the Environmental Code contains provisions on liability for investigation and remediation of areas so polluted that they can cause injury or harm to human health or the environment. The main rule is that the so-called operator, the one that is operating or has operated or has taken an action that has contributed to the pollution, is responsible for investigations and remediation. A property owner may be a liable part (SEPA, 2006).

3.3 Remediation paths

There are hence three remediation paths in Sweden, the grant-funded path (1), the supervision path (2) and the exploitation path (3). The main governing rule for all three paths is the Environmental Code but there are some differences between path (2) and path (3) in relation to the aim of the remediation. Path (2) is governed by the Environmental objectives while path (3) is mainly governed directly by the Environmental Code. Section 3.5 describes the aims and working methodology for paths (1) and (2) and section 4 focuses on path (3).

3.4 Active parties in remediation

There are mainly four active parties in remediation: the Swedish EPA, the county administrative board, the municipality and exploiting companies. Their roles and responsibilities are described below.

The Swedish EPA is working nationally, internationally and provides guidance

In the process of remediation of contaminated sites in Sweden, the EPA is responsible for:

- Coordination and prioritization, on a national level
- Provide guidance on the inspection under the Environmental Code
- Administer the grant for the investigation and remediation of contaminated sites
- Monitor and evaluate the impact of the grant
- Report to the government and the EU

- Participate in European and international forum.

The county administrative boards conduct inventory, supervise and guide municipalities

The county administrative boards drive much of the remediation work. They work with:

- Overall regional employment and regional priority
- Inventory and risk classification of potentially contaminated sites
- Distribution of grants
- Studies and reports
- Regulatory and supervisory guidance
- Plan matters
- Examination of environmentally hazardous activities

Each county will present its work on remediation, and the future plans in a regional program that is sent to the SEPA. The County Board is the authority for appeals of municipal affairs.

The municipality supervises and may be the principal for state-funded projects

Many local authorities are working actively with the remediation work. The work includes:

- Studies and reports
- Beneficial ownership of contributions financed actions
- Monitoring and notifications
- Plan matters

The municipality works primarily with their own regulatory objects, as well as principal at the grant-funded remediation. A municipal enforcement case often begins by an operator on a voluntary basis who have carried out a soil testing and found contaminants.

Many remediation measures are implemented in the context of exploitation, for example, when converting an old industrial area into a residential area.

Operators take the initiative to the investigation and remediation

If an operator or property owner discovers contamination on their property they are obliged to notify the supervisory authority concerned. Many large companies carry out some form of environmental audit to assess environmental risks. In the annual report the company takes up their environmental liabilities and reports including the cost of repairing a contaminated site (SEPA, 2011).

3.5 SEPA's starting points of remediation

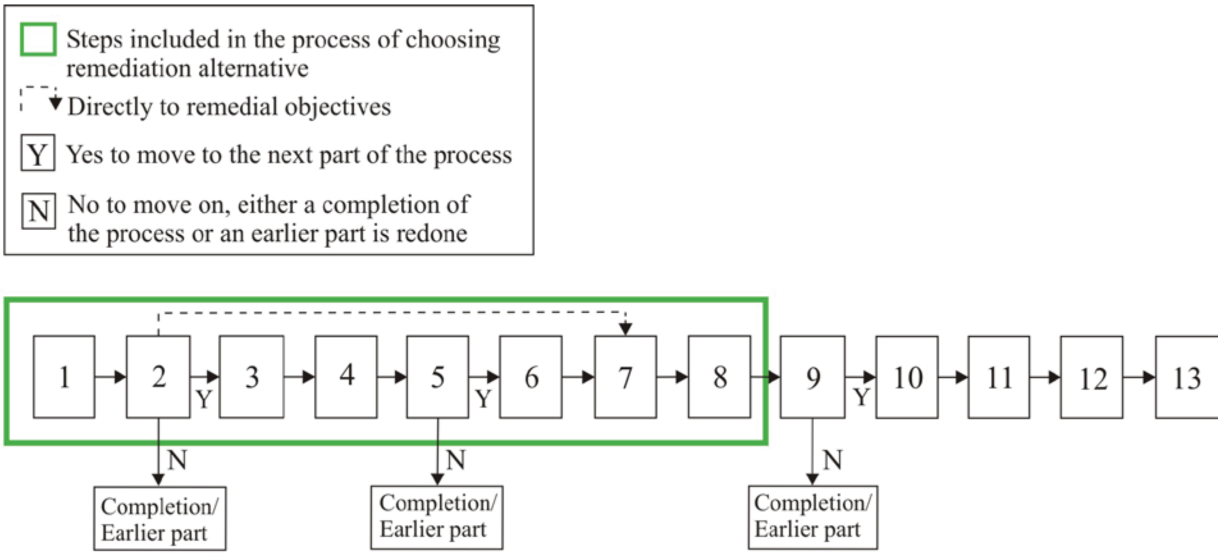
SEPA states 7 starting points to be considered in the remediation processes (SEPA 2008). The starting points are formulated in accordance with long-term thinking and sustainability in an attempt to protect human health, the environment, and natural resources at the present and in the future. The 7 starting points are:

1) Evaluation of environmental and health risks at contaminated sites should be performed in both short and long-term perspectives.
2) Ground and surface water are natural resources which always are worth protecting.
3) Dispersion of contaminants from a contaminated area should neither result in a raise in background levels nor a risk that the amount of pollution, in the long run, will deteriorate the surface and ground water quality.
4) Sediment and water environments should be protected so that no disturbances arise on the aquatic eco system and species that are especially valuable and worthy to preserve should be protected.
5) Ground environments should be protected so that all the functions of an eco system can be maintained to the extent that is necessary for the planned land use.
6) There should be an aim to have equal protection levels inside an area which as a whole has the same type of land use, for example a residential area.
7) The exposure from a contaminated area should not alone stand for the whole amount of exposure that is tolerable for a human.

3.6 SEPA's way of choosing remediation alternative

The aim of a remediation process, according to Naturvårdsverket (2009a), is to decrease risks for human health, the environment and natural resources, associated to the contaminated site to a level that is acceptable. All measures that decrease risks, contamination levels and other negative effects of the contaminated site are remedial actions which should as far as it is possible be sustainable in the long run.

The guidance on how to chose remedial measures presented by Naturvårdsverket (2009a), lists a step-by-step working methodology starting with formulation of remediation goals (see 3.4.1) to quantifiable remedial objectives (see .3.4.6). Figure 3-1 shows a flowchart that describes a working methodology of the process of choosing remediation alternative. The description includes decision steps as well as working steps. Feed-back is possible between different steps, e.g. from the feasibility study and the remedial alternative selection process back to the risk assessment (Naturvårdsverket, 2009a). Numbers of sub-sections in fig. 3-1 refer to the sub-sections in this chapter. The guidance is mainly written to guide remediation of governmentally financed remediation processes. However it is also guiding when the remediation is initiated by for example redevelopment by a construction company since the controlling agency tends to follow this guidance (Naturvårdsverket, 2009a).The description of the working methodology (3.4.1 to 3.4.9) is solely from Naturvårdsverket (2009a).



1 Formulation of remedial goals (3.4.1)
2 Decision on surveys and investigations
3 Surveys and investigations (3.4.2)
4 Risk assessment (3.4.3)
5 Decision on need of remediation
6 Remedial alternative evaluation process (feasibility study) (3.4.4)
7 Remedial alternative selection process (3.4.5)
8 Proposal of quantifiable remedial objectives (3.4.6)
9 Decision on implementation
10 Preperation of remedial alternatives and specific remediation requirements (3.4.7)
11 Implementation
12 Follow up and documentation (3.4.8)
13 Decision on completion

Figure 3-1. Flowchart showing the working methodology and decision steps in the process of choosing remediation alternative. Section numbers refer to sections in this literature review. The figure is amended after Naturvårdsverket (2009a).

3.6.1 Formulation of remediation goals

The remediation goals are a description of the aims with the remedial action. They primarily show what kind of land use or function the land is planned to have after the remedial action. They also consider disturbances that can be accepted and the land use of today. These goals can be described as a risk reduction, reduction of contamination spreading to the surroundings, decreased exposure or protection of land use or other interests.

3.6.2 Surveys and investigations

Surveys and investigations are the foundation for evaluating if any risks towards human health and the environment are present on a site. They also investigate if it is necessary to reduce these risks with a remedial action. If it is, later in the risk assessment, determined that the area compose a risk, extended surveys and investigations might be needed. Surveys and investigations mainly cover information about the contamination situation and the natural and built environment.

3.6.3 Risk assessment

Risk assessment is the identification and quantification of possible risks associated to the site of investigation (contaminated site). The risk assessment is the starting point for a decision on whether a remedial action is needed or not. The risk assessment work describes risks today and in the future, how much they have to be reduced and what form of risk reduction that is needed in short and in long term. The risk assessment includes a description of what the remedial action should focus on; transport pathways, sources of contamination, exposure pathways or protective objects. One guidance report (Naturvårdsverket, 2009b) is devoted to the risk assessment of contaminated sites because it is such an important step in choosing a proper remedial action.

3.6.4 Remedial alternative evaluation process (feasibility study)

In the evaluation process an investigation is performed to single out appropriate remedial alternatives for the contaminated site. The starting point for the evaluation process is the remediation goals and the risk assessment. The evaluation process is of fundamental importance when moving on to the remedial alternative selection process. The evaluation process includes identification of possible remedial alternatives and an analysis of them. The outcome is a set of possible remedial alternatives. Valuation criteria are used when analysing possible remedial alternatives. The selected remedial alternative must reach the remediation goals. Some alternatives may be discarded in the first process, (1) *initial analysis of alternatives*, because of technical unsuitability or unacceptable results. Categories of criteria evaluated in this analysis are: remediation goals, stakeholders' prerequisites, technical feasibility and achieved results. The alternatives left after the first round of valuation undergoes a second valuation, (2) in *depth analysis of alternatives*. Categories of criteria in this analysis are costs, risks during and after remediation and effect on the surroundings.

3.6.5 Remedial alternative selection process

Next follows a process of selecting between the remedial alternatives which are the product of the evaluation process. The selection process is founded in the formulation of remediation goals and the result from surveys and investigations, risk assessment and the evaluation process. The remedial alternatives of interest are compared, preferably through an MCA, to each other by using evaluation criteria in the following categories: target achievement in respect to risk reduction for environmental and health risk, target achievement in respect to protection of natural resources and other interests, technical aspects, economic aspects and soft parameters like impact on public and private interests. It is important to perform the selection process in cooperation with the decision maker, authorities and sometimes also the general public. The result is interpreted in the selection process and the outcome is a consideration of, on one hand the total environmental consequences and technical risks and on the other hand the costs of the remedial alternatives. The outcome of the selection process is a decision basis to choose the most appropriate remedial alternative.

3.6.6 Proposals of quantifiable remedial objectives

Quantifiable remedial objectives are a concretization and a quantification of the remediation goals. The quantifiable objectives should be several and have a close connection to the remediation goals. Some remedial alternatives need quantifiable objectives for the remedial process as well as for the result. The quantifiable objectives should always be checked for target achievement by implementing control programs. These should include controls on performance and surroundings as well as a reference survey.

3.6.7 Preparation of remedial alternatives and specific remediation requirements

The actual performance of remediation is prepared through formulating specific remediation requirements. The aim with these requirements is to guide and steer contractors in their performance to secure that the remediation goals and the quantifiable remedial objectives are fulfilled. It is important to have detailed and computable remediation requirements that comprise all activities connected to the remedial action.

3.6.8 Follow up and documentation

An easy to follow documentation of the remedial process is crucial. The documentation should include the whole process from setting the remediation goals to the actual remedial action and the follow up of it. Aspects to be covered by the documentation are scientific, technical and economic. The documentation is mainly used by the authorities to evaluate the process or as a part of the risk communication.

3.6.9 Information

Among the most important issues to consider is how information to the public and authorities is handled throughout the process of remediation. It is likely that a larger remedial action will draw attention and concern from the neighbours, surrounding citizens and also the wider society through media. If this is to be expected, then it is important to have a plan how to deal with issues from the beginning. A plan for information to and from authorities is probably also necessary in a larger remediation project.

4 Construction companies and remediation

Several construction companies in Sweden have large building projects where former industrial sites are transformed into residential areas. This is a common type of project in middle sized to large cities in Sweden since these cities undergoes a condensation due to the high demand on new areas for residential housing and offices. In the vicinity of Gothenburg, areas like Norra Älvstranden and Kvillebäcken are worth mentioning. There is also an incentive from the cities, e.g. Gothenburg, to have a sustainable development of the city which includes a wish to build on sites that already have been used instead of taking new land into use. The new land could instead be used for something else than to build residential houses or offices on, e.g. green areas for city citizens.

The companies know that there are risks involved when building on e.g. (1) former industrial sites, (2) disposal sites with excavated soil, or (3) sites with filling material, since these sites might be contaminated. The contaminations can either come from a point source (e.g. on an industrial site) or as a more diffuse contamination (filling material).

Exploitation risks of such sites can be e.g. project risks as delays due to remediation or a worse contamination situation than could be foreseen. Since there is a limited amount of money reserved for remediation, a delay could have serious consequences for the whole building project. There is also a risk of stigmatisation of the property, see figure 4-2, which in the worst case could result in a situation where it is to sell the apartments. It is hence important to have a good understanding of the risks and opportunities present in a construction project on a contaminated site.

4.1 From acquisition of land to the building of a residential area

The success in an acquisition of a contaminated land for redevelopment into a residential area or an office area, hence involves different processes. It is firstly the actual building process, and connected to that, the environmental issues which are highly important to consider in these kinds of acquisitions. As in any land development project, project risks are present but for cases of developing a contaminated site, risks connected to the actual contamination and the way they are handled are of high importance.

Figure 4-1 gives a generic figure of the building process, environmental issues and project risks possibly present in exploitation projects where contaminants might be present in soil and/or ground water.

Figure 4-1 shows the interconnections between the building process, environmental considerations and project risks. The green arrows from environmental issues and project risks pointing towards the building process emphasise at what stages in the building process these issues are addressed. The environmental considerations are handled by an environmental specialist whereas the building process and project risks are mainly considerations made by the decision-makers of the property development. The interconnections have been divided into risks during the *(a)* preparation phase, *(b)* implementation phase and the *(c)* follow-up phase.

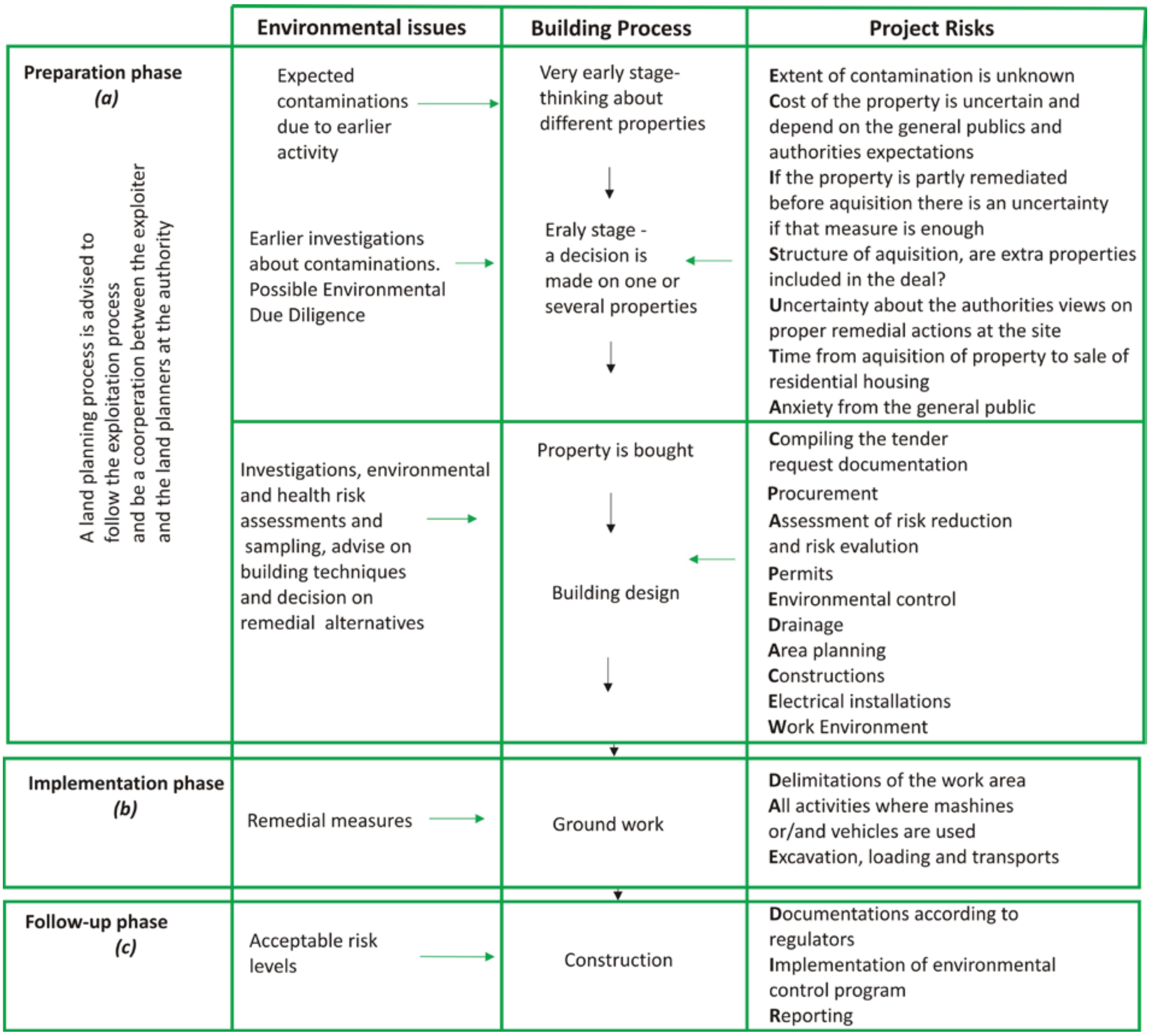


Figure 4-1: Generic figure showing the interconnections between environmental considerations and project risks which are present during different stages of the building process. The generic figure is compiled after personal communication with Ingemar Bengtsson and Malin Norin at NCC, Rosén and Wikström (2005), a project reference group meeting (2011) and Naturvårdsverket (2006).

4.1.1 The building process

Preparation phase (a)

At the very early stage in the building process a review of possible properties takes place and a number of properties are identified. These properties should be located at a close distance to the city centre and/or have good communications. Location is hence an incentive to buy a contaminated site (Bengtsson, 2010). Other incentives could be a cheaper price than an uncontaminated property or a scarcity of available properties (Norin, 2010). In bigger cities in Sweden these properties are e.g. former industrial land or sites with filling material with none or less known contamination. At this stage a rough calculation is compiled which includes numbers on how much it would cost to purchase and develop the property of interest compared to the expected willingness to pay for the houses (Bengtsson, 2010).

For the properties where the rough calculation looks promising, an investment calculation is done. Risks are well accounted for in this kind of calculation. In the investment calculation, a value is calculated on e.g. how much it will cost to purchase the property, remediate and build on it. This value is compared to the expected market value of residential units. The estimation on how much it will cost to remediate a property gives the developer a remedial cost-space to spend on remediation, Figure 4-2.

The impact of detrimental conditions such as contamination on a property value has been investigated by Bell (1998). He developed several detrimental condition models for different situations. Figure 4-2 shows his full detrimental conditions model, which includes costs before, during and after remediation. In the figure, (A) is the unaffected property value at the specific site and (B) shows how the property value is affected by the actual contamination, (C) is the assessment of the contamination and (D) the remediation. (E) is e.g. monitoring of the site after remediation have been completed and (F) is the possible remaining impact of any market resistance, i.e. stigma effects (Bell, 1998). The remedial cost-space could be interpreted as the difference between the costs of purchasing a contaminated site (B) minus the costs of assessing, remediating and monitoring the site (C-E).

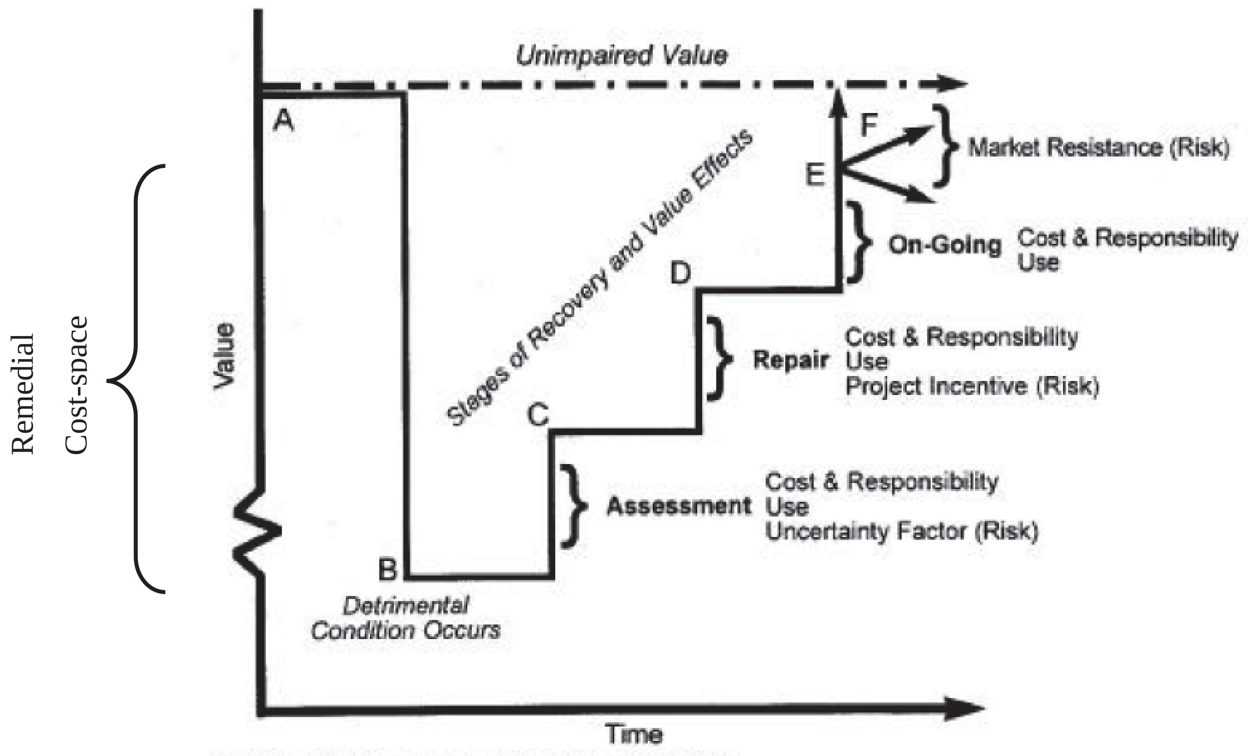


Figure 4-2: *Detrimental Conditions Model by Bell (1998).*

The estimations about the contamination situation result in risks which can negatively affect the entire project later in the process. Knowledge about e.g. contaminations, soil profile, ground water, earlier activities, etc. in the beginning of a building project is necessary, to be able to maximize the economic outcome of a building project at a former contaminated site (Norin, 2010).

After the investment calculation, properties which are not economically lucrative are discarded. The properties left are investigated further e.g. through an environmental Due Diligence (see 4.1.2) (Bengtsson, 2010). When a property is purchased the process of developing the future land use and building design starts, a process that is important to coordinate with the detailed land planning process.

A former industrial site, which a developer is interested in changing into a residential area, must first be developed according to the Plan- och Byggnadslagen (PBL) from one type of land use to another. This process, the detailed land plan process is preferably performed in cooperation and in coordination between with the land planners at the authority and the developer. The detailed planning process always includes a consultation with the general public and other concerned parties (Naturvårdsverket, 2006).

It is also emphasized by Naturvårdsverket (2006) that when exploitation drives the process of the detailed land plan the remediation should be performed before or at the same time as the plan is executed since the detailed land plan guarantees the land as fit to use according to the plan. If remediation is performed after the detailed land plan is executed and a problem is discovered, e.g. a more severe contamination situation than was expected, it might result in a necessary remaking of the plan and a time delay of significance (Naturvårdsverket, 2006).

Implementation (b) and Follow-up phase (c)

Ground work is conducted during the implementation phase; this can be a combination of work connected to the remediation, and e.g. environmental excavation and ground work as a preparation for the house constructions. The houses are constructed in the follow-up phase.

4.1.2 Environmental issues

Preparation phase (a)

Before acquisition, the issues concerning environmental conditions on a property differ depending in what stage the building process is (Figure 4-1). In the early stages when no decision is taken on which property to buy, the questions concerns e.g. what type of contaminants to expect and the result of earlier investigations (Bengtsson, 2010). At this stage there might of value to the purchasing company to have an Environmental Due Diligence performed to retrieve more information about the property of interest.

Environmental Due Diligence is primarily a decision support to the management of the purchasing company, and secondary a support in contract negotiations between buying companies and selling companies. A Due Diligence can be more or less depending on, for example how large or complex activities the target company practices or how well a buyer knows the company, market or industry. The process of due diligence includes an environmental site assessment including: (1) record review of former activities on site and in the surroundings that might have contaminated the property, (2) site reconnaissance by both visual and physical observations on site to evaluate the environmental condition, and (3) interviews with current and past owners about former activities on the site. It is not within the scope of such investigation to collect samples or submitting samples for analysis. The result of the investigation is reported to the buyer of the property (Mester, 2000).

Later stages of the building process, after acquisition, include environmental investigations about type, extent and levels of contaminations through sampling. This procedure enables an establishment of the risk of contamination. Further are remedial goals decided and the remedial alternatives selection process is performed to decide on how, with what strategy and technique, to handle the risk, Figure 4-1. All these efforts aim at lowering risk levels until an acceptable risk level is reached and the area is fit for building on, residential houses, offices or parking spaces. These processes are further described in section 3.4.

Implementation (b) and Follow-up phase (c)

In the implementation phase, the actual remedial measure is implemented and followed up by assuring that acceptable contamination levels and remedial goals have been achieved. It might be necessary to implement some sort of environmental control program to monitor that e.g. no contaminations is leaching out, if still present in the ground, from the property.

4.1.3 **Project risks**

Preparation phase (a)

The examples of project risks given in Figure 4-1 are from Rosén and Wikström (2005) and a reference group meeting within the research project of which this study is a part of. The project risks shown in Figure 4-1 are risk events that might compose a high or low risk depending on the probability that they occur and the consequence if they do.

Risks in the very early stages of the building process, before the property is bought are e.g. connected to the economic valuation of the contaminated property and how the contamination situation and remediation will affect the final value of the property (Figure 4-2).

One project risk that was indicated by the reference group meeting as important was the situation with an unknown response from authorities on the measures of a contaminated site. It was pointed out that how the authorities handle a case with a specific contaminated property is unknown for the property developer beforehand. It is according to the reference group regional differences between authorities thus making the situation different depending on what part of Sweden the property of interest is located. This is also discussed by Vik et al. (2001). They highlights that a purchase and a remediation of a property can be, according to the developer, done in a cost-efficient way but since the regulators do not have cost-effectiveness as an aim with the remediation they therefore become a project risk (Vik et al., 2001).

Some risks given in the preparation phase in Figure 4-1 are risks which can be present throughout the whole project, e.g. the actual extent of the contamination, anxiety from the general public and the uncertainty if cost of the property will turn out to be too high compared to the cost for investigations and remediation.

Implementation (b) and Follow-up phase (c)

Risks during the implementation phase concern activities during the ground work at the site e.g. where machines are used during excavation, loading or transporting. Here are also risks with workers work environment such as emissions and dust. Also in this phase, the consequence of having chosen the wrong remediation technique falls out. These consequences, e.g. not being able to meet the remediation goals, can cause a delay in the remediation which can turn out to be very costly for the construction company. Examples of risks in the follow-up phase are documentation and reporting risks or during implementation of environmental control programs.

4.2 Legislative framework during ground work prior to construction

There are some legal aspects to be aware of, both before and during ground work, when handling contaminated soil prior to construction of e.g. residential houses. The regulations to follow and permits and notifications to provide to authorities while conducting ground work, are mainly based on regulations by the Environmental Code (EC) in the ninth tenth, eleventh and fifteenth chapter (see Table 4-1).

Table 4-1: Governing parts of the Environmental Code, for construction projects, during the presence of possible contaminants. Adapted after Borgart (2010) and Naturvårdsverket (2006).

EC Chapters	Term	Description
2	General rules of consideration	
10	Responsibility of contamination damage	Environmental damage through pollution of land or water, a building or facility may result in damage or harm to human health or the environment.
9	Environmentally hazardous activities Notification requirements for remedial measures	Any use of land, buildings or facilities in one way or another that can result in discharges to water, air or land or other risk of harm to human health or the environment. This description is applicable to the handling of soil (waste) during construction. Storage of soil, sorting and mechanical processing (e.g. crushing), recycling of soil for engineering purposes, disposal of soil, e.g. to landfill and transportation are all considered environmentally hazardous events and demands either a notification or permit depending on amounts of soil. Authorization and notification requirements to hazardous activities are documented in an appendix to the regulation (1998:899) concerning environmentally hazardous activities and health *. *All remedial measures which may increase risk of spreading or exposure to contaminants shall be notified to the regulator. A notifiable activity may commence no earlier than six weeks after the notification has been made. Water discharges, such as pumped water, is a notifiable hazardous activity
11	Water activities	Water activities, such as excavation or filling of wetlands, dredging, drainage of groundwater or soil water may need a permit or notification
10; 11§	Disclosure Obligation	Duty to immediately inform the regulatory authority when the discovery of a contaminant on a property and the contamination can cause damage or harm to human health or the environment. This refers to property owners and users, such as developers and entrepreneur.
15; 1§	Waste definition	Any object, material or substance included in a category of waste (under the Waste Regulation) to which the holder discards or intends to discard or is required to discard. Classification of waste is done according to the waste regulation in non-hazardous and hazardous waste.

5 Remediation strategies and techniques

This section is an overview of remediation techniques used in Sweden based on an inventory made by Helldén et al. (2006) of 226 remediation projects. 90 projects were carried out on closed gas stations by SPIMFAB (SPI Miljösaneringsfond AB) and the other 136 were financed through authorities as municipalities and state agencies or private problem owners. Additional techniques added to the overview are taken from the Treatment Technologies Screening Matrix from the Federal Remediation Roundtable in the USA (FRTR, 2008). Furthermore, descriptions of techniques are from Rast (1997), Helldén et al. (2006), FRTR (2008) and Hamberg (2009).

An Ex-situ remediation strategy implies excavation of soil or sediment or pumping groundwater to be treated either on-site or off-site. Less contaminated soil and sediment can be excavated and disposed of without treatment i.e. off-site disposal. In-situ strategies are per definition on-site treatments where soil, sediment or groundwater is treated while still in the ground. Containment of contaminations in the ground can be viewed both as a strategy and an in-situ technique.

5.1 In-situ and ex-situ remediation techniques

Remediation strategies are, as stated before, divided into ex-situ, in-situ and containment strategies. There are three main types of remediation techniques:

1. Concentration
2. Destruction
3. Immobilization

Concentration techniques concentrate the contaminants before disposal, containment or destruction. Destruction techniques destroy contaminants and alter them into less harmful products. Immobilisation techniques restrict contaminant movement and/or decrease bioavailability. An overview of techniques from FRTR (2008) is presented in Table 5-1 with a main division in two groups, **soil, sediment, bedrock and sludge** and **ground and surface water including leachates.** Further, each main group is divided in ex-situ and in-situ strategies as well as concentration, destruction and immobilization techniques. Containment strategies are placed under In-situ strategies and immobilisation techniques highlighted with a (C). Air emissions/Off-gas treatments are excluded.

Table 5-1. In-situ (I), ex-situ (E) and containment strategies (C) divided in concentration, destruction and immobilisation techniques (FRTR, 2008).

Soil, sediment, bedrock and sludge			
	Concentration	**Destruction**	**Immobilization**
I	Soil flushing Vacuum extraction SVE Thermal methods Electro kinetic methods Fracturing Phytoremediation	Biological degradation Thermal treatment Bioventing Enhanced Bioremediation Chemical reduction/oxidation	Stabilisation/ solidification Vitrification Landfilling (C) Cover (cap) system (C)
E	Separation (Sieving) Soil washing Thermal desorption Chemical extraction	Incineration Landfarming Biological degr. Composting Dehalogenation Slurry phase bio treatment Hot Gas Decontamination Pyrolysis Open burn/detonation Chemical reduction/oxidation Biopiles	Stabilisation/ solidification

Ground and Surface water including leachates			
	Concentration	**Destruction**	**Immobilization**
I	Air sparging Directional wells In-well Air stripping Thermal Treatment Passive/reactive treatment walls (Filter techniques and reactive barriers) Hydro fracturing enhancements Bioslurping Dual phase extraction	Monitored natural attenuation Chemical reduction/oxidation Phytoremediation Enhanced bioremediation	Deep well injection Physical barriers (C)
E	Separation Sprinkler irrigation Air stripping Pump and treat Adsorption/Absorption (Assuming pumping) Granulated Activated Carbon/Liquid Phase Carbon Adsorption Ion exchange Precipitation/Coagulation/Flocculation	Bioreactors Constructed wetlands Advanced oxidation process	

Table 5-2 shows techniques reviewed in Helldén et al (2006) arranged in ex-situ methods and methods to apprehend contaminated soil masses, concentration techniques, destruction techniques and immobilization techniques. Table 5-2 also shows what type of contaminants the different techniques are able to reduce.

Table 5-2. Remedial techniques reviewed in Helldén et al. (2006) and what contaminants they reduce. S stands for used in Sweden.

	Techniques	**Contaminants reduced**
	Ex-situ techniques and techniques to apprehend contaminated soil masses	
S	Excavation and sorting	All contaminants, metals and organic compounds
	Dredging of contaminated sediment	All contaminants, metals and organic compounds
S	Transport-elimination methods (reactive barriers used during excavation)	All contaminants, metals and organic compounds
	Concentration techniques (in-situ and ex-situ)	
S	Soil vapour extraction	VOC and s-VOC (volatile or semi volatile hydro carbons), Petrol, heating oil, jet fuel, chlorinated aliphates
S	Air sparging	Petrol, heating oil, jet fuel, chlorinated aliphates
S	Soil washing	Metals and organic compounds
S	Thermal desorption	VOC and s-VOC (volatile or semi volatile hydro carbons), PCB, Pesticides, Dioxins, Furans, Arsenic, Mercury
S	Filter technique and reactive barrier	PAH, Arsenic, Chromium, Copper, Dioxin, Mercury, PCB, Chlorinated solvents,
S	Pump and treat	Organic compounds, oil products as diesel and petrol
	Phytoremediation	Metals and organic compounds
	Electrokinetic remediation	Metals and organic compounds
	Destruction techniques (in-situ and ex-situ)	
S	Biological treatment: Bioreactor, Digestion Composting, Bioventing or Landfarming	Organic compounds as hydrocarbons in light form as petrol and jet fuel for the in-situ methods. Bioreactors can treat more hydrocarbons which are more difficult to degrade. Static landfarming can treat diesel and heating oil.
S	Combustion	Almost all organic compounds
S	Natural Attenuation	Hydro carbons
S	Chemical oxidation	Organic compounds
	Immobilisation techniques	
S	Stabilisation and solidification	Inorganic compounds as metals
S	Enclosing and barrier technique (in-situ)	Metals, organic compounds as dioxins and furans, PCB

The techniques described further in section 5.1.1 – 5.1.4 are mainly from Table 5-2 but divided according to the division in Table 5-1. Some techniques from Table 5-1 are also described. An extra emphasise has been put on describing excavation and dredging (5.1.1) since these methods are so widely used.

5.1.1 Excavation of soil and sediment

Excavation can be the single remediation technique used at a contaminated site or a prerequisite to other remediation techniques, but it can also be performed in combination with other techniques. Excavation used as the single technique with removal of soil and disposal on landfill as the end result are commonly used in Sweden. These excavations are called environmental excavations in contrast to the technical excavation performed before a construction of a building. Sometimes these two excavations interact when building on contaminated land.

Soil

Environmental excavation is often performed in benches or layers to enable continuous sampling of the underlying soil. It is possible to excavate both above and below the ground-water table. When excavating below the ground-water table, pumping of water is necessary to keep the soil as dry as possible. Excavation can be performed in different ways concerning the gentleness of the excavation. If contaminants are present in layers in the soil, it is possible to isolate the contaminated layers. This enables a gentle excavation by excavating the cleaner soil first, putting it in one pile and later excavating the contaminated layer and putting it in another pile. This procedure results in a separation of the contaminated layer from the cleaner thus enabling a possibility to send the soil to different disposal sites. Such a gentle excavation results in an environmentally and economically better situation (Norin, 2010). The main concern during excavations, besides reducing the contaminated soil volumes, is to secure the work environment since there may be risks of e.g. collapsing excavation pits, emissions and dust (Helldén et al., 2006).

Sediments

If contaminants are located in sediments, dredging is typically used to remove the contaminated sediment. Dredging can be performed in three different ways, dredging by suction, by excavation and by freezing. The sediment contains at least 75 % water, thus dewatering is always necessary before remediation of or disposal of the sediment (Helldén et al., 2006). By using e.g. Geotubes dewatering can be achieved. Usage of Geotubes have been investigated by e.g. (Magnusson et al., 2011).

Sieving and washing

Excavated material is sometimes sorted on-site by sieving before sent to disposal, treatment or reuse. Sorting achieves a reduction of contaminated material as the coarse fragments, i.e. boulders, stones and demolition waste, often are considered clean and does not need to be disposed in the same way as the finer grain sizes. Most contaminants are adsorbed/absorbed to the fine particles (Helldén et al., 2006). Sieving enables a reduction in amounts of transports off-site which has positive environmental and economic effects.

Sometimes excavation and sieving is used in combination with soil washing. Water is typically used to wash the contaminated soil. Contaminants are sorbed onto fine soil particles and soil washing separate them from the bulk soil. It is thus a system based on particle size. The wash water needs to be taken care of and can be considered as waste. It may be augmented with a basic leaching agent or chelating agent or by a pH adjustment chemical to help the removal of organics and heavy metals from the water. Soil and wash water are mixed ex situ on site in a tank or in another treatment unit.

Classification

The excavated soil can be reused on-site, off-site, treated on-site or off-site, or disposed off-site at a land-fill, Figure 5-1. The governing factor when excavating is the remedial goals which are developed using a risk-based approach. The generic guideline values are a part of the “simplified risk assessment” for the most common contaminants. These values are based on the future land use scenario where sensitive land use, e.g. residential areas have one set of values (KM-generic guideline values for contaminated levels) which have higher requirements than the less sensitive land use (MKM-generic guideline values), e.g. offices, industrial areas and parking lots. These generic guideline values govern what levels of contaminants that can be left in the ground and automatically what needs to be remediated by excavation or other techniques. In the case of excavation this equals what needs to be excavated (van Hees et al., 2008).

To decide the amounts of soil possible to classify below or above KM-generic guideline values and amounts below or above the MKM-generic guideline values the soil needs to be sampled. Sampling takes place before, during and after excavation. Before excavation, samples are taken to classify the soil, during excavation (in the soil piles) to make sure that the soil have been classified correctly for the intended disposal site and after, in the excavation pit, to assure that the acceptable contamination levels have been reached. For further reading about the value of information of further sampling to reach the optimal sampling points see Back (2006).

Samples, both before, during and after excavation, can either be taken as primary samples or composite samples. Composite samples represent a larger volume than primary samples. Composite samples are often used to cut costs or to calculate a mean value of contamination.

A mistake in the classification can result in large economic and environmental impacts. Classification mistakes can result in two cases, either is too much or too small amounts of soil excavated. Too much excavated soil results in a higher cost for disposal and transportation as well as more emissions due to larger amounts of transportation and more soil that has to be transported longer distances. Too small amounts of soil results in a situation where the remediation goal is not met. This demands a continuation of the remediation which will have delay consequences and result in economic deficits.

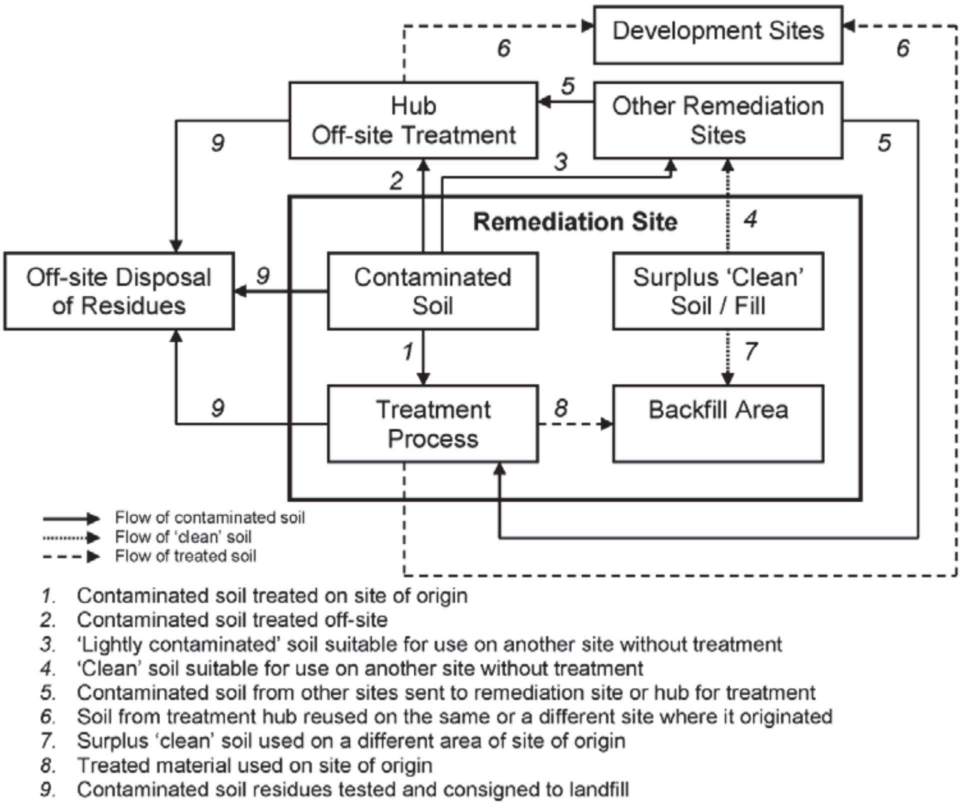


Figure 5-1. Schematic figure of possible flows, treatment, landfilling and re-use of “clean”, lightly contaminated and contaminated soil materials, from van Hees et al. (2008).

Disposal

In Sweden excavated soil and related materials is considered to be waste and is therefore listed under two entries in the “Waste Ordinance” (SFS, 2001:1063). The waste acceptance criteria (WAC) at the disposal sites govern the accepted contamination levels of the disposed soil (Van Hees et al., 2008). The contamination levels thus govern how far the excavated material needs to be transported for disposal, treatment or both since it varies between disposal sites what contaminations and contamination levels they accept. The lightly contaminated soils can typically be transported short distances but heavily contaminated soils (above level of hazardous waste) need to be transported to e.g. SAKAB in Kumla or NOAH in Norway and sometimes also needs to be stabilized through e.g. cement matrices. The costs for disposal rise, as well as transportation distance, with higher contamination levels and possible extra treatments (van Hees et al., 2008).

Transportation of excavated soil and sediment

Depending on the size of the excavated site and how large amounts of soil that has been treated on site by e.g. sieving and/or washing, varying amounts of transportation are involved. The most common type of transportation is by truck, but also train and boat transports are used. According to a review by Helldén et al. (2006), truck transportation has been used in 90 % of the reviewed cases and train and boat transports in 10 %. The environmental impacts of transportation of excavated soil have been investigated in numerous studies (e.g. Diamond et al., 1999, Hector, 2009). Suér et al. (2004) reviewed a number of LCA assessments of remediation by excavation. The conclusion was that the transportation had the main negative impact on remediation by excavation due to the large use of energy (Suér et al., 2004). Hector (2009) compared transportation means for excavated soil (boat, truck and train) and concludes that boat transports have the largest impact on the studied environmental effects categories.

The same reasoning regarding transportation is applicable to dredging thus the dredged material can be treated on-site before disposal and consequently decrease contamination levels and hence transportation distances. Sieving as treatment technique is not applicable to dredged material since it most commonly is composed of finer grain sizes.

5.1.2 Concentration techniques

Some techniques appear both in-situ and ex-situ as well as in soil and water. These are indicated with the following capital letters (S) for soil, sediment, bedrock and sludge, (W) for ground and surface water including leachates, (E) for ex-situ and (I) for in-situ.

Soil, sediment, bedrock and sludge (In-situ)

Soil flushing removes organic and/or inorganic contaminants from the soil by flooding the site with a flushing solution and later collecting the solution in shallow wellpoints or subsurface drains. The solution is then treated and/or recycled. Contaminants are mobilised during the flushing through different reactions between the flushing solution and the contaminants, such as solubilisation, forming emulsions or chemical reactions. Examples of flushing solutions are, water, acidic aqueous solutions and surfactants (Rast, 1997).

Soil vapour extraction (SVE) is mainly used in-situ but sometimes used ex-situ on-site in remediation facilities like vacuum tents. The contaminants concentrated are volatile or semi volatile organic compounds (VOC:s and SVOC:s). A vacuum pump creates a negative pressure in the unsaturated zone and the contaminant gases move from their places in the soil. When contaminants are volatilized they are collected by an extraction well installed above ground and treated through e.g. filtering. Sometimes extraction is combined with the contribution of heated air which increase the volatilization of the contaminants (Helldén et al., 2006).

Thermal Treatment (S&W, E&I) is a variety of techniques that can be used both in soil and groundwater, ex-situ as well as in-situ (USEPA, 2010). Steam or hot air injection, Figure 5-2, or electrical resistance/electromagnetic/fibre optic/radio frequency heating is used to increase the volatilization rate of VOCs and SVOCs and to facilitate extraction (FRTR, 2008).

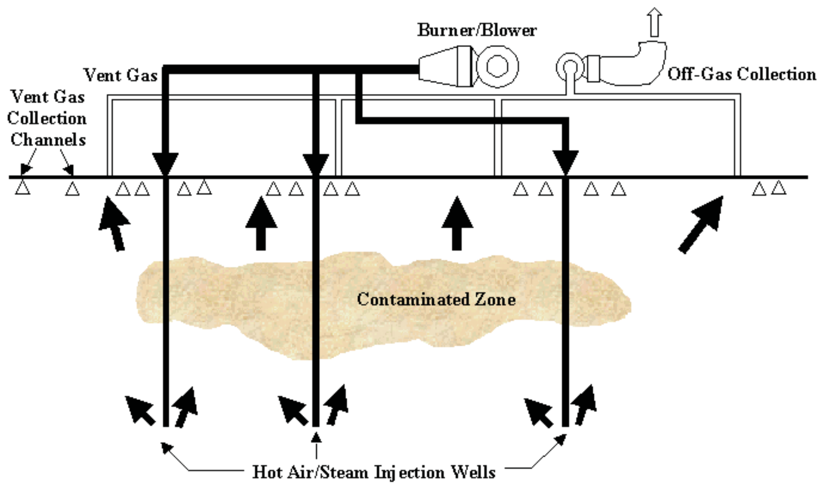


Figure 5-2. Typical Hot Air Injection System (FRTR, 2008).

Electro kinetic techniques refer to a technique using a low intensity current sent between electrodes which have been put into the ground. The current results in a voltage field and when contaminants are present as metals, the positively charged ions will cluster on the negatively charged cathode. The opposite happens to positively charged ions which clusters on the cathode. The technique is mainly applied to soils contaminated with metals but has been used also on organic contaminations. When electrodes are full of metal they are picked up from the ground and the metals are destroyed or recycled. The technique is not dependent on soil fraction but can be sensitive to organic content (Helldén et al., 2006).

Soil, sediment, bedrock and sludge (Ex-situ)

Soil washing (E&I) is mainly conducted in remediation facilities on-site. When performed in-situ the technique is called in-situ soil flushing. Water is typically used to wash the contaminated soil. Contaminants are sorbed onto fine soil particles and soil washing separate them from the bulk soil. It is thus a system based on particle size. The washing process is divided in several steps, all concentrated on separating contaminated particles and fluids from the rest of the material. The wash water may be augmented with a basic leaching agent or chelating agent or by a pH adjustment chemical to help the removal of organics and heavy metals from the water. Soil and wash water are mixed ex situ on site in a tank or in another treatment unit. Wash water and various soil fractions can be separated using gravity settling (Helldén et al., 2006).

When performing **Thermal desorption** the contaminated soil is placed in a cylindrical shaped rotating oven. Heating is direct or indirect. When direct heating is used gas or steam is run through the contaminated soil. More usual is to use indirect heating using a screw auger (in-situ) full of heated oil or fluid which is run through the soil. An electrical heated blanket on the ground can also be used to heat the soil. When heated, the organic contaminants are forced of the material and destroyed or vaporized. Temperatures between 100 and 800 degrees Celsius are usually used. The residual gases are most often taken care of by a carrier gas or vacuum system that transports the volatilized water and organics to a treatment system (USEPA, 2010; Helldén et al., 2006).

Chemical extraction is a means of separating hazardous contaminants from soils, sludges, and sediments, and reducing the volume of the hazardous waste to be treated. Contaminated soil and extractant are mixed in an extractor where the contaminants are dissolving. The extracted solution is then placed in a separator, where the contaminants and extractant are separated for treatment and further use. Physical separation steps, e.g. sieving, are often used before chemical extraction to divide the soil in finer and coarser fractions (FRTR, 2008).

Ground and Surface water including leachates (In-situ)

Air sparging is conducted in ground water contaminated by SVOC:s or VOC:s. Compressed air, nitrogen gas or oxygen is pumped into the saturated zone below the ground water table and air bubbles create transport channels through the unsaturated zone where contaminants can move upwards. The air flushes the contaminants into the unsaturated zone. Air sparging is combined with ordinary vacuum extraction or SVE to remove the generated vapour-phase contaminants in the unsaturated zone. It is also possible to use air sparging as a remediation step in chemical and biological in-situ treatments (USEPA, 2010; Helldén et al., 2006).

Passive/Reactive walls or filter techniques and reactive barriers (E&I) are used for remediation of ground and surface water. A filter made of a coarse grained matrix and a treatment media, in combination with a pre-filter with a particle separating function is used to catch contaminants in the water. The matrix has the function of keeping the filter permeable with a certain structure. The sorbent is an active substance that is participating in the sorption mechanisms in the filter. Examples of sorption materials are active coal/granules, bentonite, calcium carbonate, highly humificated peat or iron rich soil/iron. The sorption processes are mainly used for treating inorganic contaminants even though some sorption mechanisms also might be useful for organic contaminants (Helldén et al., 2006).

Reactive barriers are constructed in the saturated zone below the ground-water table downstream the contamination plume. Common designs are either a continuous trench where the reactive material is backfilled. The trench is perpendicular to the contamination plume. Another commonly used arrangement is a funnel and gate system. Walls of low permeable material (funnels) lead the contaminated water to the permeable treatment zone (the gate). The barrier can consist of activated coal to adsorb organic contaminants or some kind of ion exchange material as chelators, zero-valent iron to take care of metal contaminants (USEPA, 2010; Helldén et al., 2006).

Bioslurping or **Dual Phase Extraction** is a technique very close to pump and treat in its design. The free phase of a petroleum product is removed with the help of creating a vacuum. When extracting under vacuum, the risk of the contamination moving vertically is almost zero. After extraction from the remediation well the water-petroleum mixed fluid passes a fluid divider where water and air is separated. The air is then transported to a carbon filter while the petroleum contaminated fluid is diverted to an oil separator(Helldén et al., 2006).

Ground and Surface water including leachates (Ex-situ)

Air stripping (E&I) is a technique where VOCs as TCE, benzene, toluene, xylene and methyl chloride are removed from water. The most used stripping system is the packed tower, Figure 5-3, which forces air bubbles through the contaminated water and the contaminants, gets transferred from the water to the air. The air must be treated after stripping the water and this is done through the use of activated carbon adsorption, catalytic oxidation and thermal desorption (Rast, 1997). Air stripping can be performed in wells in-situ as well as ex-situ.

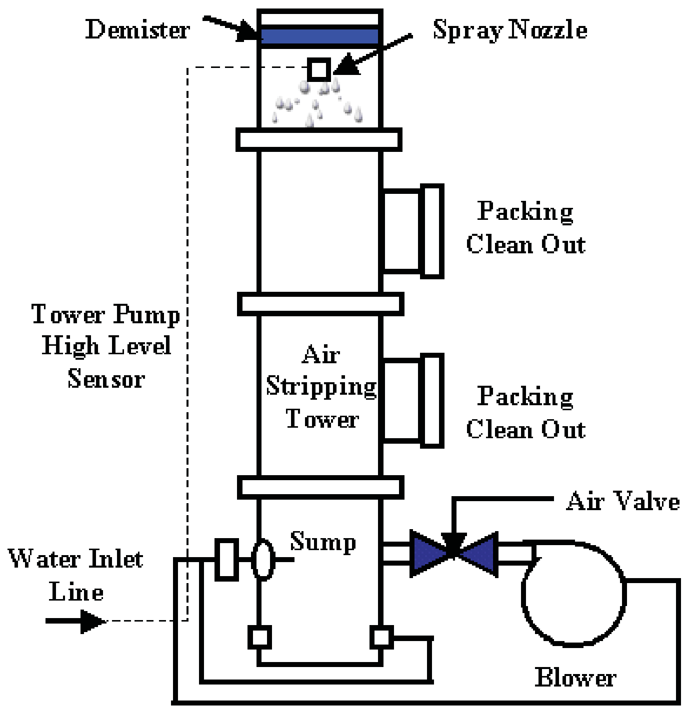


Figure 5-3. Air stripping system (FRTR, 2008).

Pump and treat is one of the most commonly used techniques for treating contaminated groundwater. Today it is often combined with other techniques as biological and chemical degrading, air sparging or reactive barriers. Ground-water is pumped to the surface where the water is treated typically with filter techniques (e.g. active coal). Air stripping can be used in combination with pump and treat to separate VOC:s. After the water has been treated, it is recharged into the saturated zone or diverted to a surface water recipient. Pump and treat can also be used when there is a need to stop a contamination plume from spreading (Helldén et al., 2006).

Sprinkler irrigation is a relatively simple treatment technology used to volatilize VOCs from contaminated wastewater. The process involves the pressurized distribution of water with VOC through a standard sprinkler irrigation system. VOCs are transformed from the dissolved aqueous phase to vapour phase (FRTR, 2008).

5.1.3 Destruction techniques

Some techniques appear both in-situ and ex-situ as well as in soil and water. These are indicated with the following capital letters (S) for soil, sediment, bedrock and sludge, (W) for ground and surface water including leachates, (E) for ex-situ and (I) for in-situ.

Soil, sediment, bedrock and sludge (In-situ)

Biological degradation (I&E) is not one single technique but a generic term for a group of techniques aiming at converting organic compounds to simpler less toxic organic compounds or to a complete degradation where the end product are the inorganic compounds carbon dioxide and water. The conversion takes place in a micro-biological way. Bacteria that consume organic compounds are dependent on the presence of carbon, hydrogen, nitrogen, phosphorus and oxygen. Hydrocarbons in e.g. petroleum or creosote can be a source of nutrients for the bacteria. Nitrogen, phosphorus and oxygen have to be added to stimulate the natural digestion of petroleum by bacteria present in soil.

Biological degradation uses the help of oxygen and nutrients to degrade the petroleum. In-situ methods can be used both below and above the ground-water table. Bio degradation performed below the ground-water table mainly reduces contaminants in the pore water (Helldén et al., 2006).

Bioventing is a form of biological degradation where ventilation of the ground is performed with a low air pressure, i.e. oxygen is forced into the ground, Figure 5-4. The technique is used for stimulating degradation of hydrocarbons. The method is applicable to any organic contaminant that can be aerobically biodegraded. There are some characteristics that are limiting the use of bioventing and other biodegrading techniques; soil grain size and soil moisture are the most important. A combination of high water tables, high moisture and a fine-grained soil can make the technique infeasible (USEPA, 2010).

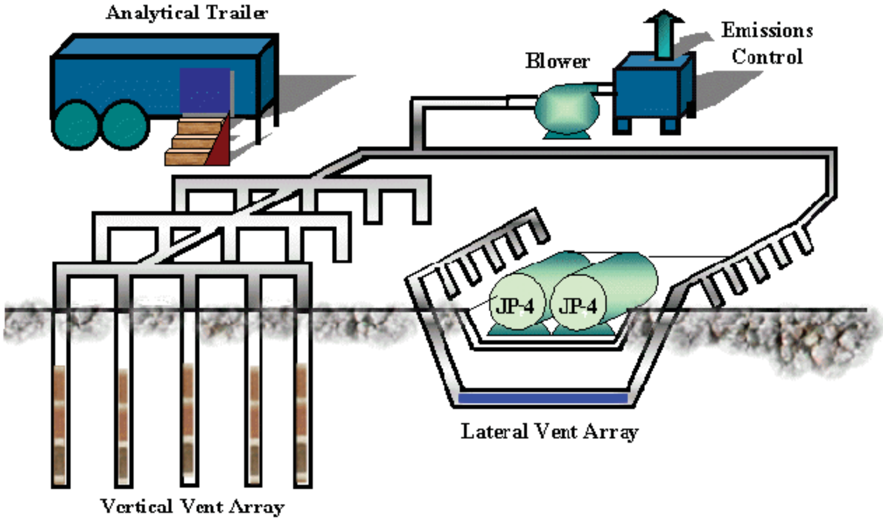


Figure 5-4. Bioventing system (FRTR, 2008).

During **Enhanced bioremediation (S&W)** is the activity of naturally occurring microbes stimulated by circulating water-based solutions through the contaminated soil. This process enhances *in situ* biological degradation of organic contaminants or immobilization of inorganic contaminants. The end products of organic compounds as well as inorganic will vary depending on if it is aerobic or anaerobic conditions during degradation. One may use nutrients or oxygen to enhance bioremediation and contaminant desorption from subsurface materials (FRTR, 2008).

Phytoremediation (S&W) uses the ability of plants to adsorb, degrade, volatilize or accumulate contaminants. Contaminants can be present in, soil, sediment or ground-water. It is mainly metals that plants can take up with their roots but some organics can be bound to plant tissue. Metals like micronutrients as Cr or Cu are taken up by plants but also others as Pb and As can also be adsorbed. In other cases contaminants are stabilized in the soil or on the roots. The different forms of Phytoremediation are; Phytosatbilization (contaminants are bound to the root surface or cells), Phytodegradation (degradation of organic compounds), Phytoaccumulation (uptake and accumulation of contaminants in roots and leaves), Phytovolatilization (root uptake and transpiration of organics), Rhizodegradation (degradation and transformation of organic contaminants by the activity of rhizosphere) and Evapotranspiration (Combination of evaporation and transpiration from leaves where the end product is water) (Hamberg, 2009).

Chemical reduction/oxidation (S&W&E&I) is a destruction technique that can be used on ground-water or soil, ex-situ and in-situ. Where an oxidizing agent is added to the ground-water it spreads in the water through injection wells. Reduction/oxidation (Redox) reactions chemically convert contaminants to less toxic compounds that are more stable, not as mobile, and/or inert. Redox reactions involve the transfer of electrons from one compound to another. Specifically, one reactant is oxidized, loses electrons, and one is reduced and gains electrons. Examples of oxidizing agents are ozone, hydro peroxide, carbon dioxide or oxygen. In soil and ex-situ treatment is the oxidizing agent mixed with the excavated soil. If full oxidation occurs the contaminants will be transferred to carbon dioxide and water. If ozone is used the end product is alcohol, aldehyde, ketones, and carboxylic acids (USEPA, 2010; Helldén et al. 2006).

Soil, sediment, bedrock and sludge (Ex-situ)

Incineration is a biological treatment that has been used for a long time. It destroys non hazardous waste and hazardous waste, Figure 5-5. In the presence of oxygen, explosives and organic constituents in hazardous wastes, particularly chlorinated hydrocarbons, PCBs, and dioxins are destroyed (FRTR, 2008).

The technique is often used as a destruction method of waste from concentration techniques like soil washing, thermal desorption and vacuum extraction. During combustion the organic contaminants are converted to inorganic residual products.

Two main facilities can be used, rotating oven or a fluorescent bed. The temperature for the oven is approximately 1200 to 1400 degrees Celsius and for the bed 800 to 900 degrees. These temperatures are substantially higher than during thermal desorption since the aim is to combust the material and not just force contaminants from the soil (Helldén et al., 2006)

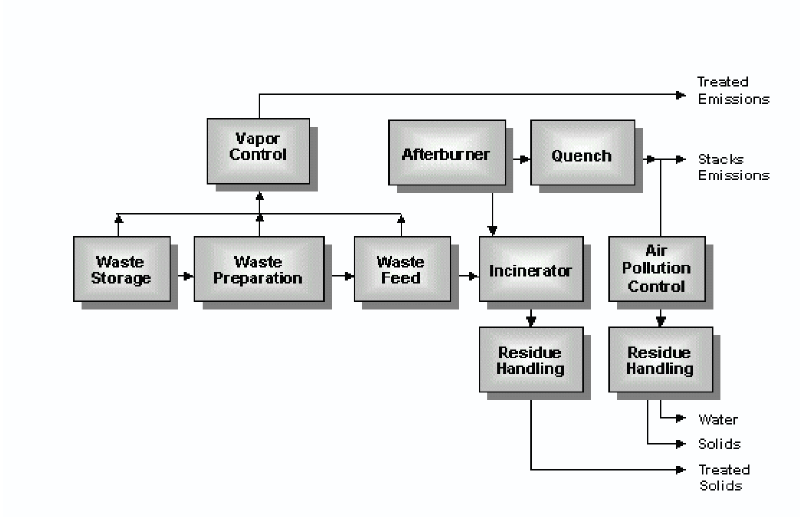


Figure 5-5. The Incineration process (FRTR, 2008).

Excavated soils can be mixed with soil amendments and placed in closed **Biopiles** above ground. The composting process is aerated with blowers or vacuum pumps see composting and landfarming below (FRTR, 2008).

Composting is an ex-situ technique where air/oxygen, nutrients and sometimes bacteria are added to the excavated soil. A filling material which works as a structure improvement is sometimes added to the excavated soil to increase the permeability of the soil. Examples of structure improving material are bark, wooden chips and straw. If bacteria are added it is in the form of horse or hen manure (Helldén et al., 2006).

Landfarming is a form of composting where strings of, or thin layers of the contaminated soil is spread out and nutrients, air and water are added. It is either an open or static technique. Strings are open and layers are static. An impermeable layer below the contaminated soil stops leachates from the farming area and the water that is recovered can be used again. The soil is turned over by a machine for aerating the soil when the “open technique” is used. The thin layers have air space between them where pipes with holes blow air into the soil to help with aeration (Helldén et al., 2006).

Target contaminant groups for **Dehalogenation** are halogenated SVOCs and pesticides. The contaminated soil is screened, processed with a crusher and pug mill, and mixed with reagents. This mixture is then heated in a reactor. The dehalogenation process takes place by either the replacement of the halogen molecules or the decomposition and partial volatilization of the contaminants (FRTR, 2008).

Pyrolysis is formally defined as chemical decomposition induced in organic materials by heat in the absence of oxygen. Organic materials are transformed into gaseous components and a solid residue of fixed carbon and ash. Because it is impossible to achieve a completely oxygen-free atmosphere some oxygen will be present in any pyrolytic system which results in a nominal oxidation. If volatile or semivolatile materials are present, in the contaminated soil, thermal desorption will also occur. Pyrolysis typically occurs under pressure and at operating temperatures above 430 °C. The pyrolysis combustion gases, from pyrolysis of organic material, as carbon monoxide, hydrogen and methane require further treatment (FRTR, 2008).

Ground and Surface water including leachates (In-situ)

Monitored natural attenuation is, as the name reveals, a technique where the natural degrading or attenuation processes of contaminants in the ground are monitored. Some characteristics need to be fulfilled for the attenuation to function by itself. Some of these are pH, oxygen level and temperature. Monitoring includes soil and groundwater sampling, carbon dioxide measurements, aerobe and anaerobe respiration, registration of explosive gases like methane and detection of other VOC. MNA works best if the source of contamination has been removed (Helldén et al., 2006).

Ground and Surface water including leachates (Ex-situ)

In a **bioreactor** contaminated soil is mixed with water to slurry that is possible to stir. It is necessary to adjust the pH-value, moisture level and nutrients so the most favourable conditions are created. The slurry is kept either in a container or a dam with an impermeable layer in the bottom. Treatment in a container needs usage of electricity and water and an area between 200 and 900 m^2. Microorganisms are added continuously or before the treatment starts. The containers can also be used when treating pumped ground-water (Helldén et al., 2006).

In **Constructed wetlands,** influent water with high metal concentrations and/or organic contaminants flows through and beneath the gravel surface of a gravel-based wetland, Figure 5-6. Metals are removed through ion exchange, adsorption, absorption, and precipitation with geochemical and microbial oxidation and reduction. The wetland is using plants in a coupled anaerobic and aerobic system. The anaerobic cell uses plants together with natural microbes to degrade the contaminant. The aerobic plant improves the water quality further through continued exposure to the plants and the movement of water between cells. Wetland treatment is a long-term technology and need to be in operation continuously for years (FRTR, 2008).

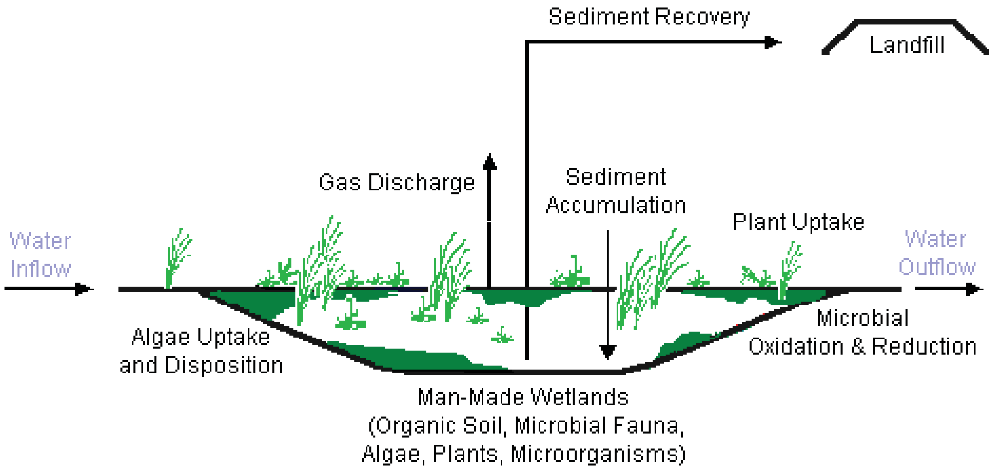


Figure 5-6. A constructed wetland system (FRTR, 2008).

5.1.4 Immobilisation techniques

Some techniques appear both in-situ and ex-situ as well as in soil and water. These are indicated with the following capital letters (S) for soil, sediment, bedrock and sludge, (W) for ground and surface water including leachates, (E) for ex-situ and (I) for in-situ.

Soil, sediment, bedrock and sludge (In-situ and Ex-situ)

Stabilisation/solidification (E&I) refers to two immobilisation techniques that are quite similar and often occur at the same time. Stabilisation is mostly a chemical process where an additive reacts with the contaminated soil and contaminants are made less mobile/leachable. Solidification is a process where soil is capsulated and turned into a structure that is immobile and with low leakage ability and low permeability. Examples of additive are bentonite, cement, lime, formaldehyde, polyesters, fly ash, and urea. The additive most often used in stabilisation is cement which will lead to a decreased leakage and reduced permeability. Mixing of additive to soil for stabilisation or solidification can be done both in-situ and ex-situ (Helldén et al., 2006, Hamberg, 2009).

The **Vitrification (only in-situ)** process is an electrically melting of the contaminated soil. The temperatures vary between 1600 and 2000 °C. Electrodes are placed in the ground and a mixture of graphite and glass is put between the electrodes on the surface to start the melting since soil is a poor conductor in itself. When the surface starts melting the heat is transferred to the soil below. At certain very high temperatures the soil and contaminants undergoes physical changes and decomposition reactions. Organic contaminants vaporise and pyrolysis takes place since there is no oxygen present. When the heating is stopped the volume of soil cools down during a long period, moths to a year and the soil is the solidified. Clean soil is placed above the monolith after cooling (Rast, 1997).

Soil, sediment, bedrock and sludge (Containment)

Landfilling Cover/ cap system are used for contaminant source control according to the following:

- Minimize exposure on the surface of the waste facility.
- Prevent vertical infiltration of water into wastes that would create contaminated leachates.
- Contain waste while treatment is being applied.
- Control gas emissions from underlying waste.
- Create a land surface that can support vegetation and/or be used for other purposes.

The design of landfill caps is site specific and depends on the intended functions of the system. Landfill Caps can range from a one-layer system of vegetated soil to a complex multi-layer system of soils and geosynthetics. The material used in the construction of landfill caps includes low- and high-permeability soils, low-permeability geosynthetics products, fig. 5-7, as well as a cover of vegetation or a drainage that harvests water on top of the landfill cap. Water harvesting can be performed by covering the landfill surface with metal rain gutter placed parallel to the slope which enhance the run-off in that direction. The vegetation cover or water harvesting reduces or eliminate percolation, the effects of run-off and/or evapotranspiration (FRTR, 2008).

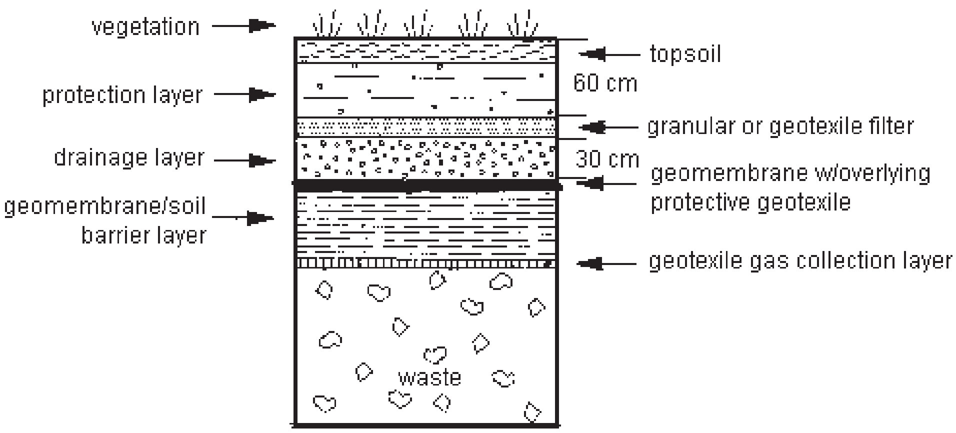


Figure 5-7. Landfill cap system (FRTR, 2008).

Enclosing and barrier technique (E&I) is a technique mainly applied if no other remediation technique is possible. It is also possible to use disposal/enclosing on the concentrate after other remediation techniques such as soil washing or small amounts of contaminated soil with very high contamination concentrations. Enclosing imply that the contaminated soil is closed within a barrier material which will reduce the amount of water and oxygen to reach the contaminants. The barrier is divided in different layers both at the bottom and on the top. The bottom layers contain a liner, a draining layer and a geotextile. Underlying the top sealing layer, e.g. a clay layer, is draining layer (Helldén et al., 2006).

Ground and Surface water including leachates (Containment)

Deep well injection is a disposal technology where liquid waste is injected into a well situated in a geologic formation which has an impermeable zone both at the top and bottom. This prevents the contaminated waste to migrate to any aquifers. The casing of the well is filled in with cement all the way back to the surface in order to seal off the injected waste from the formations above the injection zone back to the surface (FRTR, 2008).

Physical barriers are similar to **Passive/Reactive walls or Filter techniques and reactive barriers**. The physical barriers trenches are filled with slurry of soil, bentonite and water, Figure 5-8. The slurry acts as wall stabilization during excavation of the trench. Later the trench is backfilled with soil and bentonite. The soil bentonite filling is for stopping movement of contamination in the groundwater. It acts as a cut off wall due to its very low permeability. Best success has been achieved if the base of the wall is vertically placed in a low permeable material e.g. clay. A cap is placed on top of the wall (FRTR, 2008).

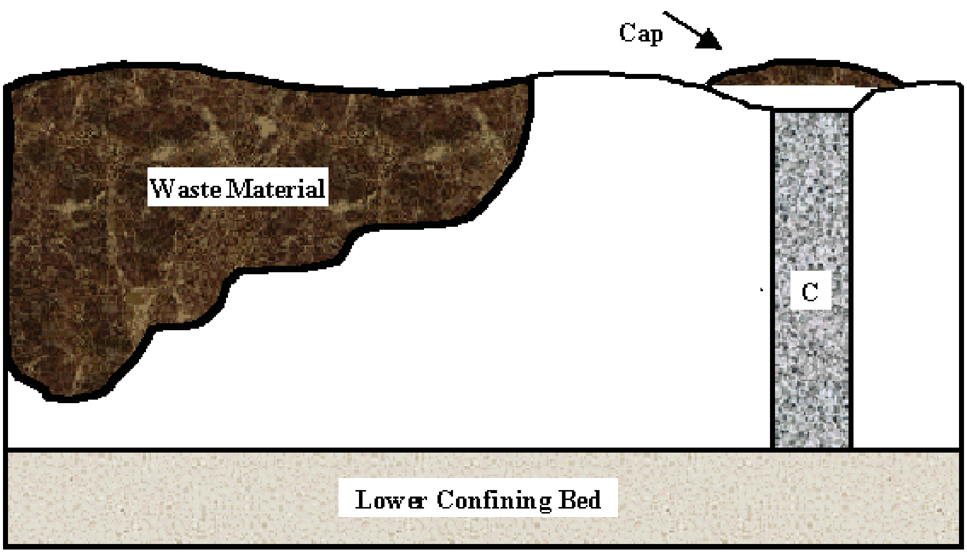


Figure 5-8. Physical barrier (FRTR, 2008).

6 MCA and MCDA as decision support in remediation

“Decisions do, and should, depend on outcomes and probabilities, on stakes and odds, on values and uncertainties.” (Von Winterfeldt and Edwards, 1986).

If politicians, government employees, construction companies or ordinary people find themselves in a situation where a decision has to be made regarding any issue there are certain ways to structure and find help in the decision making process. The first important step is to think about the objective: what or where is the decision aiming? The next step is to find the alternatives and the key factors of relative importance by which the alternatives will be judged (Belton and Stewart, 2002).

There are several ways to go about the analysis step of evaluating how alternatives meet the objective. One way to analyse the alternatives is by using monetary based techniques, e.g. CBA or CEA. CBA is an assessment of all the costs and benefits of each alternative and CEA is an assessment of the costs only, see further in section 6.2. Another way to analyse alternatives is to use MCA or MCDA. CBA and CEA can be a part of an MCA/MCDA or they can be used as the sole analysis technique. These procedures will hopefully lead to a transparent and understandable decision aid where the alternative that best meet the objective is sorted out (CLG, 2009).

6.1 Outline of the MCA methodology

An MCA is a method for making the decision process transparent and structured thus providing decision support, when there is a large amount of complex information. MCA can be used for different purposes: (1) to identify a most preferred alternative, (2) to rank alternatives against each other, (3) to short-list a set of alternatives, (4) to group alternatives or (5) to distinguish the acceptable alternative from the unacceptable (CLG, 2009).

There are according to CLG (2009), several advantages with an MCA over informal judgement. These advantages are:

- It is open and explicit.
- The choice of asset of objectives and criteria that any decision making group may make is 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. Scores and weights provide an audit trail.
- Performance measurement can be sub-contracted to experts, so they 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 a wider community

CLG (2009) states further that:

“For projects of major public concern, it is crucial to obtain inputs from a variety of professionals and have the implementation of the methodology monitored and routinely reviewed by independent experts.”

An MCDA involves all 8 steps shown below. For less complicated decisions, it is possible to only use steps 1 – 4 and 7 for the analysis, which is then in this section referred to as an MCA. An MCA ends with a performance matrix while the MCDA includes scores, weights and the combination of these into an overall value for each alternative. To separate an MCA from an MCDA the steps below that reside in an MCDA only are highlighted with bold letters (CLG, 2009).

1. Establish the decision context. What are the aims of the MCA, and who are the decision makers and other key players?
2. Identify the decision alternatives.
3. Identify the objectives and criteria that reflect the value associated with the consequences of each alternative.
4. Describe the expected performance of each alternative against the criteria. **If step 5 and 6 are included, this performance should be measured quantitatively by scores or other units.**
5. **Assign weights for each of the criteria to reflect their relative importance to the decision.**
6. **Combine the weights and scores for each of the alternatives to derive an overall value.**
7. Examine the result.
8. **Conduct a sensitivity analysis of the results to changes in scores or weights.**

6.1.1 Step 1 – Decision context and key players

Step 1 in an MCA is to establish the decision context. This is done by defining the overall aim or objective, and by identifying the persons, institutions and historical context that defines the decision situation. Further, the persons affected by the decision and those responsible for it are identified, i.e. stakeholders and decision makers (CLG, 2009).

The overall objective describes the purpose of the analysis. A clear and well structured objective facilitates the analysis of alternatives and the opposite may result in the analysis not answering the question (CLG, 2009).

The definition of a stakeholder is according to the Cambridge Dictionaries (2011), a person or group of people who own a share in a business or a person such as an employee, customer or citizen who is involved with an organization, society, etc. and therefore has responsibilities towards it and an interest in its success. Stakeholders in remediation projects are e.g. general public, regulatory agencies as SEPA, non-governmental organisations (NGOs), private site-owners, public site-owners or contractors (Norrman, 2004).

Belton and Stewart (2002) discuss the identification and involvement of different stakeholders in the decision-making process. Depending on the aim of the process there is a question of whether it is desirable and/or possible to involve representatives from all stakeholder groups or not. If the aim is to get knowledge of different perspectives on an issue the involvement of all groups is considered to be important and in such a case, all stakeholder groups' views should be considered.

According to Eden and Ackerman (1998), it is not obvious that the decision-makers are interested in involving all stakeholder groups to a discussion because of fear for sabotage of the decision. There might also be considerations from decision-makers about stakeholder involvement since stakeholders are not in isolation of each other, they can influence each other or go in coalition.

The risk communication strategies of today, advice decision- makers to identify all stakeholder groups and that they are well aware of the legal requirements or policies that may limit the design of the risk communication. Decision-makers should also (1) have a clear awareness of the purpose of communication, (2) determine the characteristics of the target audience to be able to (3) select the strategy that serves the purpose at hand, e.g. the use of explanatory tools or choice of participatory and communication format (workshops, meetings, interviews etc.). This is considered by risk analysts to be the best way to prevent expressions of dissatisfactions (Burgman, 2005).

6.1.2 **Step 2 – Identification of decision alternatives**

When the objective is established, alternatives are identified, **step 2**. An important step when deciding on alternatives is the sifting step where alternatives are left out if there is a legal or other restriction against that alternative (CLG, 2009). Belton and Stewart (2002) describe the process of generating alternatives as fundamental in structuring and building the MCDA model. Sometimes it is quite straight forward and easy to produce clearly defined alternatives but other times some work has to be focused to this subject. Belton and Stewart (2002) give direction to references that focus on the alternative generating process e.g. Keeney (1992).

6.1.3 **Step 3 – Identification of criteria**

In **step 3**, criteria and sub-criteria are defined. Criteria aim at describing different parts included in the objective and sub-criteria do the same for criteria. The smaller and hence measurable parts, the sub-criteria, aim at analysing how well the overall objective is met by the different alternatives. All multi-criteria methods include an identification of key factors to be used in the evaluation of alternatives. According to Belton and Stewart (2002), the nomenclature of these key factors is varying depending on what MCA method is used. They can be referred to as: values, (fundamental) objectives, criteria, or (fundamental) points of view. Box 1 (p.47) presents a discussion about terminology. In this report, the terms: overall objective, criteria and hence first and second level sub-criteria are used.

The extent to which an alternative meets the outlined objective as set up by the decision makers, are evaluated by the use of the defined criteria. In the process of defining the criteria and the following evaluation whether the right set of criteria and sub-criteria have been chosen, a checklist or series of questions is useful. These questions can be answered by interest groups or the decision making team. In order to proceed with the defined set of criteria, the answer to all questions must be yes. If not, the set of criteria should be revised. Table 6-1 shows such a checklist (CLG, 2009).

Table 6-1. Checklist to be used when evaluating if the right set of criteria have been chosen, after CLG (2009).

Question	Yes	No
Completeness; are all criteria included?		
Redundancy; are there any unnecessary criteria included?		
Operationality; can each alternative be judged against each criterion?		
Mutual independence of preferences; is it possible to assign preference scores for one alternative on one criterion without knowing what the alternatives' preference scores are on any other criterion?		
Double accounting; are criteria independent of each other? If so, are there any criteria valued more than once?		
Size; are there any inconsistencies between the number of criteria and the likely importance of the topics they reflect?		

Belton and Stewart (2002) also discuss important aspects to think about when identifying criteria, which are valid for all MCDA methods. In addition to the questions in CLG (2009) they note that it is important to think about the following:

- **Value relevance**; a direct link between a criterion and the concept it is suppose to capture (value).
- **Understandability**; all decision makers have a shared understanding of the concepts to be used in the analysis.
- **Measurability**; it is possible to specify, in a constant manner, how the performance of alternatives against criteria is going to be measured.
- **Simplicity vs. complexity**; the criteria structure is the simplest one, still able to capture the complexity of the decision it tries to describe.

Box 1. Terminology in MCDA and sustainability appraisal.

Methods that use value functions, e.g. Multi-Attribute Value Theory (MAVT), typically try to identify a hierarchy of criteria or a "value tree". This is also the case when using the Analytical Hierarchy Process (AHP). MAVT is a further development of Multi-attribute Utility Theory (MAUT). This is more thoroughly described in section 6.2.1. However, Keeney and Raiffa (1993), the original developer of MAVT, use the terminology objectives, attributes and sub-attributes.

Other types of methodologies, i.e. outranking methods, use the terminology "key criteria", which can be a complex construction of different sub-criteria. Yet other types of methods, like multi-objective (goal) programming, use a small number of quantitatively measurable "objectives" or "goals" (Belton and Stewart, 2002).

Indicators are a commonly used term in sustainability assessments (e.g. Therivel, 2004, Smith et al., 2010, ISO CD., 21929-2, 2010) Indicators are described by ISO CD 21929-2 (2010) as:

"figures and measures that enable information on a complex phenomenon like environmental impact to be simplified into a form that is relatively easy to use and understand."

ISO CD 21929-2 (2010) further states that the main functions of indicators are quantification, simplification, communication and to set targets.

6.1.4 **Step 4 – Performance of the alternatives**

Quantitative performance evaluations: Performance matrices

Step 4, includes the construction of a performance matrix. It brings structure and transparency to an MCA. It is often used to visualise what criteria are relevant to take into account when comparing alternatives as well as to visualise the performance of the alternatives on each criterion.

A performance matrix, also referred to as a consequence table, has an alternative on each row and a criterion in each column. Each column describes the performance of the alternatives against each specific criterion. The assessment of the alternatives can either be quantitative and qualitative, numerical or other such as "bullet point" or colour coding (CLG 2009).

Table 6-2 gives an example of different performance assessments, cardinal numbers, binary terms, and qualitative terms for alternatives between four brands of toasters.

Table 6-2. Performance matrix displaying an MCA evaluation of four brands of toasters (Rosén et al., 2009).

Criteria	**Price**	**Reheat setting**	**Warming rack**	**Evenness of toasting**	**Number of drawbacks**
Performance assessment	**(Cardinal numbers)**	**(Binary terms)**	**(Binary terms)**	**(Qualitative terms)**	**(Cardinal numbers)**
Alternatives					
Model 1	270			Good	3
Model 2	400	√	√	Good	3
Model 3	330	√		Very good	2
Model 4	300	√		Very good	5

By doing a direct analysis of the performance matrix it is possible to discover if dominance of any alternative occur. If one alternative performs at least as good as all the others and much better in at least one criterion than other alternatives it is a dominating alternative in the analysis. One reason behind dominance can be that criteria are missing from the analysis. If so, additional and relevant criteria may need to be added to the performance matrix to overcome the dominance.

The performance matrix can be the final product of the analysis and this leaves the decision makers to evaluate which alternatives meet the objectives best just by studying the performance matrix (**step 7**) (CLG, 2009).

An MCA (**steps 1-4 and 7**) with a performance matrix provides the decision makers with good basic factual information. The MCA does not provide any information about the relative importance of any criteria and it does not contribute with any supplementary information beyond what is displayed in the performance matrix.

Quantitative performance evaluation: Scoring

However, the criteria can be evaluated quantitatively by numerical values. This evaluation is always are included in an MCDA, where complex problems are handled, and are typically performed in two stages, scoring and weighting (i.e. step 5, see section 6.1.5).

Before performing scoring it is helpful to construct a hierarchical structure to assist in the organisation of criteria and to ensure that all criteria are present. This is an applicable approach when MCDA methods based on value functions are used, e.g. MAVT (Keeney and Raiffa, 1993). For AHP a hierarchy of criteria is a prerequisite. According to Keeney and Raiffa (1993), the hierarchy brings structure to the produced list of criteria. These criteria should cover all the areas of concern and the purpose behind a subdivision of criteria to sub-criteria is to clarify the intended meaning of the criteria and hence the objective. Figure 6-1 is an example of a hierarchy of criteria.

Figure 6-1 has the objective sustainable remediation, which is subdivided in the three criteria, economy, ecology and socio-culture. These criteria are further divided in sub-criteria. Social profitability or cost-effectiveness is used for the economic criterion and there are six sub-criteria for the criterion ecology. The criterion socio-cultural is sub-divided in seven sub-criteria.

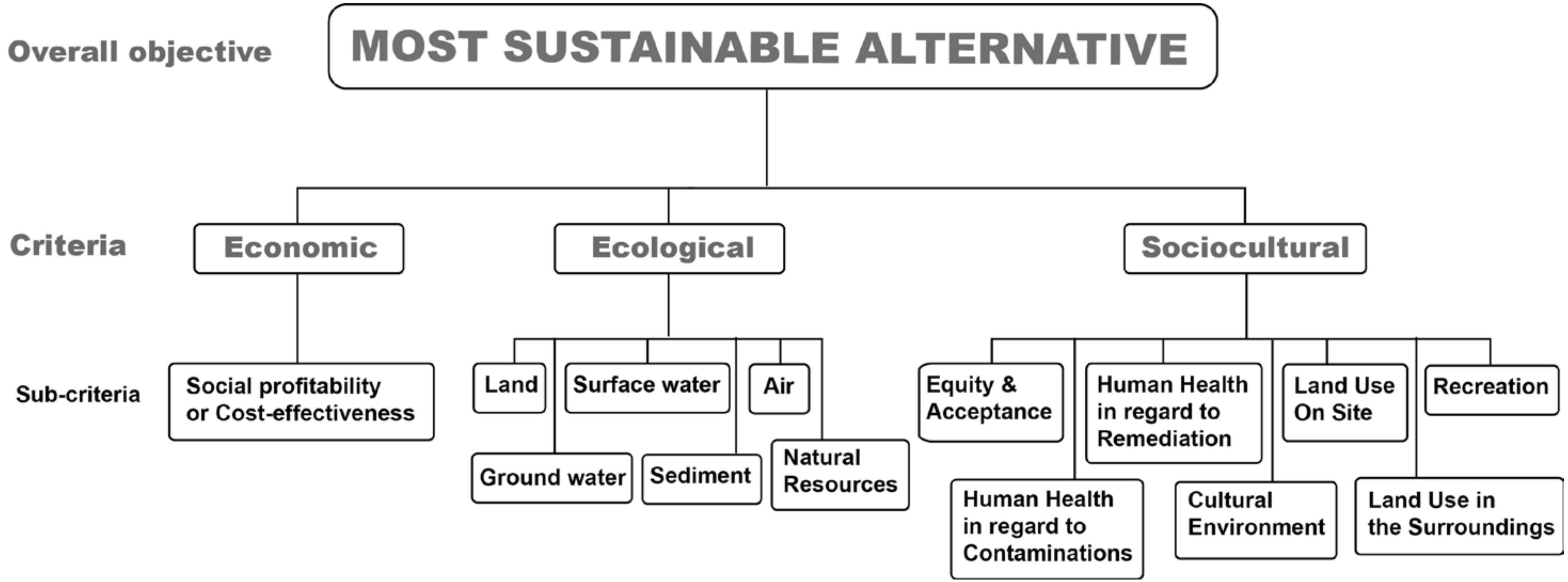


Figure 6-1. Hierarchical structure with overall objective, criteria and sub-criteria for evaluation of sustainable remediation alternatives, amended after information in Rosén et al (2009).

With each alternative follows an expected consequence on the identified criteria. A first step for evaluating that consequence is to assign reference points to the scale by which alternatives are going to be scored. The score 0 is often associated with the worst level of performance and the score 1 or 100 with the best level. The scores 0 and 1 or 100 then represent the performance interval. It is thus, for the purpose of scoring important to know something about the context of the scores. The context rules what kind of values the reference points and hence all points, in the interval between them, have. On the x-axis, in Figure 6-2, is the reference points the best and worst performance. It can be other values as e.g. money, meters or tons. If the relationship between the reference points is linear, it is possible to assign scores without converting them to scores on the y-axis via a value function (Belton and Stewart, 2002).

The reference points can either be on a local scale or on a global scale. The local scale refers to the specific set of alternatives in a specific decision context whereas a global scale refers to a wider set of possibilities. When a local scale is used the alternative which performs best on a specific criterion is assigned a score of 100 and the one that performs worst receives a score of 0. All other alternatives receive intermediate scores between these and in relation to them. In a global scale on the other hand, are the end points defined by the ideal and the worst performance of a particular criterion. Global scales demand much more work but has the benefit that it is more general, can be determined before alternatives are constructed and therefore additional alternatives can be added without any problem (Belton and Stewart, 2002).

Once the reference points of the scale have been assigned, scores can be assessed by using either (*a*) a partial value functions, (*b*) qualitative value scale, (*c*) direct rating, performed by an expert or (*d*) an indirect method i.e. pair wise assessments.

Construction of multi attribute value functions (MAVF) (*a*) is either performed with a direct or indirect assessment method. In a direct assessment, the decision maker needs to determine whether the value function is monotonically increasing, or decreasing against a natural scale, see fig 6-2, or whether the value function is non-monotonic. A non-monotonic value function can be an indication that the measure which is proposed in reality reflects two conflicting values (Belton and Stewart, 2002).

Indirect assessment of a value function assumes monotonic value functions. There are two ways of performing an indirect assessment; bisection or difference method. During bisection the halfway point between the two end-points is identified by the decision-maker. The assessment continues with the additional two points, between the respectively end-points and the halfway point. The assessment is typically performed by asking the decision-maker questions on the importance of an increase expected performance between different points compared to the expected performance between other points. The difference method is a collection of methods which have in common that the decision-maker is required to consider increments on the objectively measured scale, i.e. expected performance in Figure 6-2, and the difference in value (Von Winterfeldt and Edwards, 1986).

Value functions with thresholds, Figure 6-2, indicates that there is an expected performance which represents a point where any further increment is not very desirable and engenders less value (CLG, 2009).

The qualitative value scale (*b*) is used when it is not possible to find a measurable sub-criterion that captures the criterion. As in the construction of value functions, end points or reference points as well as intermediate points are defined. The difference between a qualitative value scale and a value function is that value scales are described with words, i.e. descriptions as e.g. bad-neutral-good for defined corresponding values.

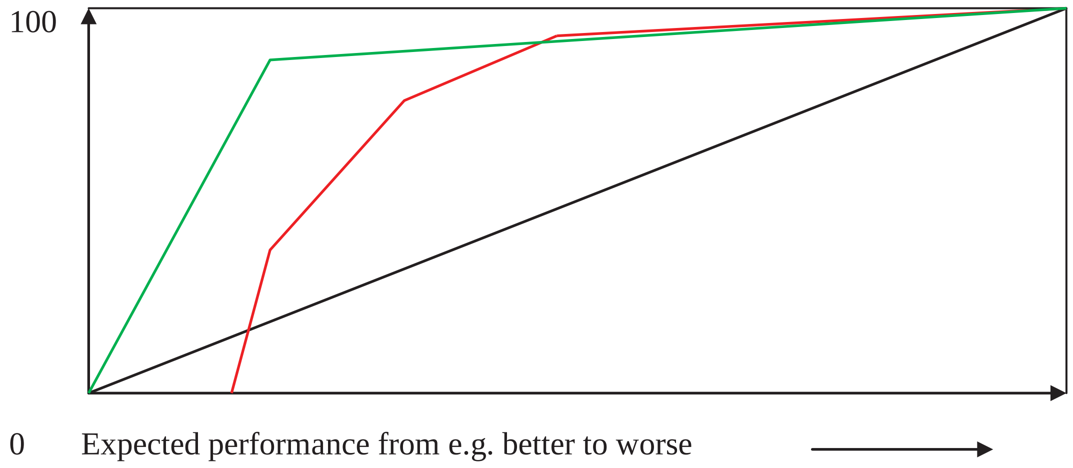


Figure 6-2. Decision on score values with help of value functions, one linear (black), one broken with threshold value (green) and a monotonic-non-linear (red). Score on the y-axis and expected performance on x-axis. After CLG (2009) and Belton and Stewart (2002).

Direct rating (*c*) is a sort of value scale where only the end points are defined. If direct rating is performed using a local scale, the alternative performing least well is given a score of 0 and the alternative performing best is given a score of 100. This does not indicate that the alternatives necessarily are bad or good in any absolute sense. Their "true" performance could have been valued using a global scale. All other alternatives are related and appointed a place on the scale in reference to these two end points (alternatives) (Belton and Stewart, 2002).

A pair wise comparison (*d*) of alternatives against each criterion generates an ordering between alternatives and a common technique to perform this comparison is AHP. AHP is further described in section 6.2.1.

An important step within criteria scoring is checking for consistency of the scores on each criterion. Even if the right number of criteria has been chosen and the chosen set fulfils all conditions, there are typically some criteria that are more important to the decision maker than others. For this to show in the analyses, and to have an impact on the final result, weighting can be performed (CLG, 2009).

6.1.5 Step 5 – Relative importance of criteria

Numerical weights, **step 5,** can be ascribed for each criterion which describes its relative importance (impact) compared to the other criteria. The weight reflects both the range of differences between alternatives as well as how this difference matters since a criterion can get relatively low weight even though it is considered very important. This could be the case if the alternatives do not differ very much in respect to one criterion. The opposite could happen if they differed very much in respect to a criterion (CLG, 2009).

Weights can be numbered e.g. from 0 to 1 or from 0 to 100 as scores are. The most important criterion gets 1 or 100 and the others are judged and assigned weights thereafter on a predefined scale, linear or non-linear (Belton and Stewart, 2002). The weighting is often performed in a group situation with experts, stakeholders or the general public.

If there are many criteria in an MCDA, a weighting technique is often used. It could be e.g. a pair-wise comparison such as AHP or the Simple Multi-Attribute Rating Technique (SMART) developed by Edwards (1971). SMART was based on prior work by psychologically-oriented researchers trying to build models of how expert decision makers make decisions. Today SMART is available with further extensions. This has resulted in SMART with swing (SMARTS) and SMART with exploiting Ranks (SMARTER). For a thorough description of SMART, see von Winterfeldt and Edwards (1986). There are several other weighting techniques, e.g. SWING and direct rating (CLG, 2009).

6.1.6 **Step 6 - Combination of scores and weights**

When scores have been assigned to all alternatives and weights on all criteria an overall value for each alternative needs to be derived through combining the scores and weights. This combination, **step 6**, can be conducted by different methods (CLG, 2009). MCDA methods differ mostly from each other in the processing of the basic information contained in the performance matrix.

The next step **(6)** in the analysis includes the decision on whether an alternative can stay in the analysis even though it performs weak when it comes to one or several criteria but performs well on one or several other criteria. An acceptance for compensation for weaker performance on one criterion results in a trade-off. These methods are compensatory methods, e.g. Multi-attribute utility models (MAUT), Multi-attribute Value Theory (MAVT), Analytical hierarchy process (AHP), and fuzzy sets (see *compensatory methods*). Another approach is to use outranking methods to facilitate the MCDA procedure. If the trade-off is found unacceptable then non-compensatory methods can be used, e.g. dominance, conjunctive and disjunctive selection procedures, lexicographic ordering and elimination by aspect (see *non-compensatory methods*).

Compensatory methods

Multi Attribute Utility Theory (**MAUT)** is the normative theory that comes closest to a kind of universal acceptance. MAUT describes how individuals should rationally choose between competing alternatives. It was developed during the 1940’s and 1950’s by the work of von Neumann and Morgenstern (1944) and later by Savage (1954) (CLG, 2009) .

These authors aimed to emanate a theory of how an alternative between choices, made by rational individuals, could be foreseen by a set of fundamental axioms of rational choice. They showed with the help of mathematics that individuals choose the alternative which gives the maximum *subjective expected utility* (SEU) value.

The SEU of an alternative is derived by going through a list of questions and calculations. First, one should identify all future states of the world that can be relevant for the decision. Second, calculating the utility u_{ij} (see formula 1.1), based on the situation where alternative i is chosen and state of the world j actually occurs. The third step is to create a probability weighted average of all the outcome utilities. The probabilities are subjective estimates derived by individuals. The estimations concern the probability that each of the outcomes actually occurs (CLG, 2009).

The utility formula (1.1) describes the utility of an alternative as follows:

$$U_i = p_1 u_{i1} + p_2 u_{i2} + \ldots + p_n u_{ix} = \sum_{j=1}^{n} p_j u_{ij} \qquad (1.1)$$

where:

U_i is the overall utility of an alternative *i*

u_{ij} is the utility of alternative *i* if, having chosen alternative *i*, and state of the world *j* actually occurs.

p_j is the subjective judgment, performed by the decision makers, of the probability that state of the world *j* occur.

There is no help available in MAUT of how the utility u_{ij} of an alternative should be evaluated. In the 1970's MAUT experienced a breakthrough by the work of Keeney and Raiffa (1993) with the **Multi Attribute Value Theory (MAVT)**.

Keeney and Raiffa (1993) contributed to the development of MAUT by providing a set of procedures that allow the decision makers to evaluate MCDA alternatives in practice (CLG, 2009). The procedures make it possible to calculate multiattribute utilities by using value functions. These calculations do not include uncertainty as the multi attribute utility theory does, since the probabilities are not included (Belton and Stewart, 2002).

Linear Additive models can be used if the criteria either is proved or assumed to be independent of each other. The linear model show how an alternatives' total weighted value (CLG, 2009). The equation of the overall performance (*V*) of alternative (*a*) is written in a similar way to equation (1.1), where w_i is the weight assigned to reflect the importance of criterion *i* and v_i (*a*) is the value score for alternative (*a*) on criterion *i* (Belton and Stewart, 2002):

$$V(a) = \sum_{i=1}^{m} w_i v_i(a) \qquad (1.2)$$

Early work with developing the linear additive model has been done by Keeney and Raiffa (1993) as well as Edwards (1971). It is useful to use the linear additive model when it is difficult to predict the alternatives performances and when the aim is to make a short list of options. The model should be combined with a sensitivity analysis to reveal what influence the weights have on the overall performance (see section 6.1.7) (CLG, 2009).

Even though the linear additive model is fairly easy to use there have been those who want to allow the model to have less precise input data. Putting less demand on the decision makers and/or making the construction and application of the model quicker can be the reasons behind such an approach (CLG, 2009). The easiest way to do this is to allow scores and weights to be replaced by statements. The statements puts a limit to the value an input can have. Typically decision makers are more uncertain about the weights than the scores. Score values can be treated as known and weights are either (1) ranked, e.g. $w_1 \geq w_2$ or (2) a limit is placed on the overall weight that a particular criteria may have, e.g. $w_3 \leq 0.25$ (CLG 2009).

Analytical hierarchy process or **AHP** was first developed by Saaty (1980) and is one of the widely applied methods to decide on values of scores and weights for calculating a overall performance of different alternatives but AHP can also be used as a scoring or weighting technique solely. Some severe criticism has been held against the method (see *limitations and pitfalls p.56*) (Belton and Stewart, 2002). The criticism has lead to attempts to derive similar methods from AHP while trying to avoid some of the difficulties with AHP, e.g. REMBRANDT and MACBETH procedures, (CLG, 2009). For descriptions of the REMBRANDT and MACBETH procedures look further in Belton and Stewart (2002).

AHP is a form of linear additive model with both scoring and weighting of scores, by comparing alternatives and criteria pair wise (Ritchey et al. 2008). The decision makers are asked to answer a set of questions about two criteria at time, e.g. A and B; *how important is criterion A relative to B?* Questions of this type are used to determine both weights for criteria and performance scores for alternatives on each of the different criterion.

Saaty's method identifies values of weights by advanced matrix algebra. The calculations are complex and there are computer programs developed to perform the weighting. However there is a possibility to calculate the weight by using the geometric mean of each row in the matrix which is the outcome of the answers of the pair wise comparisons. The answers are in Saaty's method numerical on a scale from one to nine where only the odd numbers are used. One is equally important and nine is overwhelmingly more important.

After weights and scores are computed, using the pair wise comparisons, the overall performance of alternatives is evaluated by using the linear additive model. The weighted scores, v_i, will be a number from 0 to 1. The alternative with the largest number will be the most preferred (CLG, 2009).

Outranking methods

Outranking is a quite different approach compared to the MCDA procedures described earlier. An MCDA makes strong assumptions about the underlying circumstances of the problem. Outranking seek to make fewer assumptions and is a more interactive process between model and decision-maker. The outranking method was developed in France in the mid 1960s and is mostly used in continental European countries (CLG, 2009).

Outranking is a generalisation of the concept of dominance, see page 58. Dominance in outranking is not interpreted in the same way as dominance in an MCDA, even though it is built on the same phenomenon. One alternative outranks another if it performs better than the other on important criteria and is not significantly outperformed by the other alternatives on any criterion. If an alternative show these properties it should be preferred over the other alternatives.

Outranking approaches differ from the value functions approaches in the way that there is no underlying aggregative value function. The outranking does not produce a value for each alternative but an outranking relation on the set of alternatives (Belton and Stewart (2002).

The outranking methods focus on pair-wise comparisons of alternatives. The operationalisation of outranking is divided in two phases:

1. A decision on a way to describe how one alternative can outrank another alternative.
2. The decision on how the pair wise outranking assessments can be combined so that an overall performance ranking among the alternatives can be constructed, i.e. a decision matrix that describes how the performance of alternatives can be evaluated with respect to the identified criteria.

Strictly mathematically, it is not the same mathematical definition of weights used in outranking as in an MCDA. The explanation is beyond the scope of this report, but the basic thoughts, starting-point and first step is the same. For further reading about the outranking method see, e.g. Roy and Bouyssou (1993) or Belton and Stewart (2002)

There are several outranking methods, e.g:

- Elimination et Choix Traduisant la Realite, ELECTRE I, II II, IV and TRI
- PROMETHEE (with or without GAIA)

ELECTRE I was developed by Roy in the 1960s because he was critical to the value and utility theory due to the requirement that alternatives needed to be comparable. ELECTRE is basically used to identify dominance. One alternative dominates another if it performs at least as well on all criteria and is definitely better on at least one criterion. The difference between ELECTRE I to II and III is the level of input data and the nature of the underlying problem. ELECTRE I is the earliest and simplest in the ELECTRE family, first published in 1968.

So called concordance and discordance indexes are calculated in ELECTRE I. An alternative outranks another alternative overall if its concordance index lies above the chosen threshold value and its discordance index lies below a chosen threshold value. It is the alternative/alternatives that outranks at least one other option and is not outranked itself that is searched for by using this method. For a more thorough reading about outranking and ELECTRE see Roy (1991).

The PROMETHEE method was developed by Brans and co-workers in the 1980's. This method departs in a decision matrix of evaluations of alternatives against a set of criteria just as ELECTRE does. The next step is to describe a preference function for each criterion which reflects the intensity of preference of an alternative over another alternative. It is a function of the difference in performance levels on that criterion for two alternatives. Values of this function are between 0 and 1. The PROMETHEE analysis can be visualised using a procedure called GAIA (Geometric Analysis for Interactive Aid) (Belton and Stewart, 2002).

Outranking methods can be used for both quantitative and qualitative data and a benefit of these method are the ability to recognise the political reality which can result in an elimination of an alternative that performs weak on one dimension even though it is an important and significant alternative being outranked and eliminated (CLG, 2009).

A more thorough review of the ELECTRE family and PROMETHEE can be found i Belton and Stewart (2002). Other outranking methods using quantitative and qualitative data can be found in CLG (2009).

Fuzzy sets cover methods based on an alternative or option belonging to a group or set of options that can be described in the same way. The description of the set is based on qualitative assessments as ‘expensive’ or ‘rather expensive’. Fuzzy sets were conceptualised by Zadeh (1965).

Alternatives are placed in a group and all alternatives are appointed a degree of membership between 0 and 1to the group. If the alternative has a value of zero it is the same as saying that the alternative has no belonging in the set and 1 expresses that the alternative definitely belongs to the group. An alternative can belong to a group to a certain degree; say 0.8 which is different to probability theory where a crisp line between if you are a member or not is applied.

Fuzzy MCA models uses procedures to gather fuzzy performance levels by using weights that also sometimes are fuzzy quantities. Users of the fuzzy sets stakes that there are important advantages of the method as the fact that there are concepts in a decision process which are not clear but a bit fuzzy and the method catches that reality in a good way. Some criticism exists towards these methods; see *limitations and pitfalls* below (CLG, 2009).

Limitations and pitfalls of compensatory MCDA methods and outranking methods

There are a number of compensatory methods to choose from when performing an MCDA. There are however some limitations and pitfalls with these methods that can be important to highlight. Some of these are;

- Although MCA is a tool which makes the decision process structured and transparent there will always be some form of judgement involved in it. Humans are predestined to use simplifications to better deal with complex problems. This can result in a biased decision leaning towards options that are familiar to the decision maker, recent memories or successful experiences (CLG, 2009).
- There are some aspects of MAUT which makes the method complicated; the uncertainty is built into the model and if independence between preferences does not occur, the calculating step will become very demanding. There is according to CLG (2009) no indication in MAUT of how to evaluate the utility of an alternative. This is solved with value functions (MAVF) in MAVT (CLG, 2009)
- The Linear additive model is relatively easy to use and therefore it is a risk of misuse. It is very important to follow the procedure of identifying alternatives, criteria, sub criteria and the scoring and weighting procedure. Especially critical is the weighting of criteria so that it accurately reflects the importance to the decision since improper weighting could result in an incorrect picture of how the decision makers really understand the problem (CLG, 2009).
- AHP has been much discussed because of the fact of rank reversals among other problems. The reversal can happen to original alternatives if a new alternative is added to the list. This is seen as very inconsistent and questions the whole theoretical

background of the method. The problems of rank reversal were first reported by Belton and Gear (1983) (Belton and Stewart, 2002).

- Outranking methods demand more interaction between the decision makers and the model than MCDA methods do. This is considered, by for example UK Government, to be better for non-specialists because it is more transparent and closer to the procedures of CBA and CEA (CLG, 2009).
- The fuzzy set methods have been criticised for being too difficult for non-specialists to use and having no clear theoretical foundation for modelling decision maker's preferences. There has also been criticism about the theory not showing any critical advantages in comparison to more conventional methods (CLG, 2009).

Non compensatory methods

If trade-off between criterions is unacceptable, a non compensatory method can be used. The definition of trade off is; a weak performance of an alternative, on one criterion, can be compensated by a strong performance on another criterion (CLG, 2009). Non-compensatory methods are used when an alternative with absolute demands is the objective, often with help of a rank based method (Rosén et al., 2009).

According to CLG (2009), a use of non-compensatory methods include that each alternative is evaluated against a set of criteria displayed in a performance matrix. The authors claim that a commitment to an evaluation by non-compensatory methods when outlining preferences between alternatives is in practice to severely restrict to what extent that establishment of preferences can be made.

There are however some non-compensatory methods available, **Dominance** is one. It is possible to compare alternatives in a holistic way by using dominance since it makes no assumption about the relative importance between criteria and no supplementary information is added to what is shown in the performance matrix. In practice it is not usual that dominance will be present. One alternative dominates another if it performs at least as well on all criteria and is definitely better on at least one criterion. If an alternative is dominated by all others it should be excluded and if an alternative dominates it is for sure the best alternative. The dominance approach is sensitive to data errors because of the way the answers are given, as yes or no. It is also sensitive to the removal or addition of an alternative to the analysis (CLG, 2009).

Another approach is the **Conjunctive and disjunctive selection procedures** but for this method to function the decision makers must allow one or several supplementary judgments as a complement to the information in the matrix. If thresholds are introduced for one or several criteria, the conjunctive model would exclude all alternatives that don't reach up to the externally set level of performance. The disjunctive model can allow an alternative to pass if it reaches a minimum threshold level of performance for at least one of a set of criteria.

These models work as filters and one can use both in the same decision making process, on different set of criteria. The models are according to the authors in DCL (2009) a help in giving structure and developing an audit trail when one are going from a long list of alternatives to a shorter. The conjunctive and disjunctive models can be a big help in the beginning of singling out alternatives to a short list but it is better to use other MCDA models when the alternatives are difficult to separate in terms of overall performance (CLG, 2009).

When using **Lexicographic ordering** supplementary information is provided concerning the ranking of criteria in terms of experienced importance. Each criterion is considered all over again and alternatives can be eliminated. The alternatives are first compared in terms of the most important criterion. If one alternative is much better than all the rest this is the most preferred. If this situation does not happen, and there is a tie between two alternatives, there will be another round with the next most important criterion for those two alternatives. This will proceed until a most preferred option is found.

Elimination by aspect combines the factors in both the conjunctive/disjunctive models and the lexicographic ordering. A threshold is set and the alternatives are compared against this, criterion by criterion. The ones that do not pass the threshold are eliminated. The criterion is not ordered by importance but according to what criterion has the perceived likelihood to eliminate most alternatives.

6.1.7 Step 8 - Uncertainties and uncertainty valuation

Uncertainty valuation is an important part of the construction of an MCDA model. There are different types of uncertainty; typically two different types are recognised, natural variation (aleatory uncertainty) and lack of knowledge (epistemic uncertainty) (Bedford and Cooke, 2001).

Uncertainties in MCDA

According to Belton and Stewart (2002), uncertainties related to multi-criteria decision aid can be divided in internal uncertainties and external uncertainties. Internal uncertainties are related to the process of problem structuring and analysis and external uncertainties are referring to the lack of information or knowledge about consequences of different choices.

Belton and Stewart (2002) states that there are internal uncertainties connected to the problem structuring which are resolvable and others which are not. The latter can be such matters as impression or ambiguity of meaning for a criterion. Examples of unresolvable internal uncertainties can be unclear definitions of alternative courses of action which leads to a uncertainty about which alternatives to chose. This problem can be solved by restructuring the model and it is because of this reason that iteration in the MCDA process is very important, the opportunity to go back in the process and change parts that do not work.

Internal uncertainties related to the analysis itself can be in the areas of elicitation of values and use of the model. Such uncertainties are typically assessments of performance with respect to specified criteria or the discussion about acceptable trade-offs between performances on different criteria.

Uncertainties in in-data, the scoring and weighting process as well as including uncertainties about expert judgements are therefore related to the internal uncertainty (authors note).

The external uncertainties are according to Belton and Stewart (2002) differentiated between uncertainties related to the decision area and uncertainties about the environment.

Sensitivity Analysis

Postle et al (1999) highlight the importance of dealing with uncertainties in the MCDA model. Sensitivity analysis is a useful tool when performing that task. They suggest that the sensitivity analysis for the combination of CEA and MCDA consider aspects of:

- Impact scores (using levels of uncertainty)
- Weights within categories (i.e. between sub-categories)
- Weights between impacts occurring during remediation , and those occurring after remediation
- Weights between categories (i.e. relative importance of human health and safety, environment etc.)
- Costs

Postle et al. (1999) suggests different procedures of checking the sensitivity of the above stated parts of an MCDA, e.g. changes to scores, changes to weights and applications of weights between during and after remediation.

Uncertainties in in-put variables can be modeled with the use of Monte Carlo simulations. Random numbers are used to sample values from probability distributions representing the input variables (Lindhe, 2010). According to Bedford and Cooke (2001), the difference between uncertainty analysis and sensitivity analysis is that the former investigates the importance of variables for a function and the latter the uncertainties in them.

6.2 CBA and CEA

The MCDA can be carried out without the input from a CBA or a CEA but if there are costs and benefits that could be valued in monetary terms these should be used within a Multi Criteria Decision Analysis (MCDA) (CLG, 2009).

CBA is based on well-developed economic theory of valuation based on willingness-to-pay or to accept. It is the willingness-to-pay of those who will benefit from an alternative and the willingness to accept compensation of those who will loose from the selection of a specific alternative that is valuated i monetary terms. It is the alternative or project that has benefits exceeding the costs that are the preferred one. There are many different valuation techniques in CBA. Two techniques widely used are hedonic price techniques and stated preference method.

CEA is an assessment of costs and not benefits. All costs connected to different alternatives that achieve the objectives are assessed. In this method non-cash opportunity costs can be included as well as external costs (CLG 2009).

If an MCDA does not include a Cost Benefit Analysis (CBA) but instead a Cost Effectiveness Analysis (CEA) there is no necessity that benefits should exceed costs. This is a limitation of the use of CEAs in MCDA since it could lead to the outcome that doing nothing can be the preferable option (Rosén et al., 2009).

7 Applications of MCDA to assess remedial alternatives

MCDA can be used in a remediation process as an assessment method of remediation alternatives. The purpose of using MCDA is then to compare remediation alternatives against each other to find the best alternative. What is perceived to be the best alternative is based on how an alternative performs against the criteria in the MCDA. The criteria describe the remedial objectives or the overall goal of a remediation.

The following section is a review of international and national examples of the use of MCDA in remediation. The aim has been to find articles and other sources using MCDA for evaluating remedial alternatives on contaminated land. In some cases, the sustainability of the alternatives was also evaluated. The process of studying these articles has been performed using six criteria. They were chosen to represent important information to be retrieved from the articles for the review in this report. The following criteria were set up:

- Aim or objective
- Criteria
- Method
- Application area
- Operationality
- Uncertainties

The aim or objective of the investigation and in what context the investigation is performed is important to establish. Further, the most important criteria for this review are: criteria of the investigation, what kind of MCDA are used to assess remedial alternatives to each other and how the authors have dealt with the uncertainties of the analysis method and in data.

The review in this report is divided in different sections: review papers, MCDA applications on sustainability assessments of remediation alternatives, MCDA in soil remediation and sediment management.

7.1 Examples of MCDA in remediation

7.1.1 Reviews

There is a vast amount of reviews of MCDA methods and other decision support techniques used during decision-making in environmental management of contaminated land, contaminated sediment and contaminated groundwater. The following section is an overview of reviews mainly concerned with contaminated land and sediment.

Onwubuya et al. (2009) reviews the available decision support methods and tools in terms of their fitness for purpose for the application of “gentle” remediation technologies. “gentle” refers to less invasive, alternative remediation options such as phytoremediation, in situ immobilisation etc. MCA, Life-cycle analysis (LCA), CBA and CEA are introduced. A critical review of existing decision support tools used in the UK, Germany and in Sweden is presented in the article. There is also an overview of the soft-ware based support systems/tools used across Europe such as: DESYRE, PRESTO, CARO, ROSA among others, and a review of what criteria they address are listed. Criteria examined are risk assessment, cost, sustainability and socioeconomic factors. Onwubuya et al. (2009) conclude that the only decision support tool that cover all criteria are DESYRE (see page 73 in this report for a description on DESYRE) (Onwubuya et al., 2009).

Kiker et al. (2005) gives a review of the literature available about applications of MCDA in environmental decision making. There are several aims stated in the article but the most important for this literature review is a summary of the most common MCDA methods used in practice in different application areas. The application area of greatest interest to this study, where decision support tools in environmental management have been used, is the environmental/remedial technology selection.

Kiker et al. (2005) present interesting work by others, e.g. (1) Prato (2003) and (2) Hämäläinen et al. (2001) in the application area of environmental management. The methods used are: SMART for the case with cleaning up the Milltown Reservoir/Clark Fork River superfund site (1), MAUT in the selection of management alternative Missouri River (2). These are based on real cases connected to dealing with risks with contamination of sediments in water, ecosystem management for a river system and water resource management. Kiker et al. (2005) lists the application of decision support tools for contaminated sites, see appendix 4 (Kiker et al., 2005).

Janssen (2001) gives an overview of the type and complexity of decision problems supported by MCA and the corresponding MCA approach selected to analyze these problems. There is a list of examples of the use of MCA in Dutch Environmental Impact Assessment (EIA) projects in the paper. The overview covers activity, year, problem size and MCA method. Weighted summation is the most used MCA method (10 times used). Janssen (2001) also report on a case where an MCA have been challenged in court. The case is about a storage facility for polluted sediments (Janssen, 2001).

Wenstøp and Seip (2001) propose criteria for evaluating legitimacy and quality of Environmental Policy. A review of five MCDA applications for environmental policy in Norway is presented with the aim to find a clear relationship between legitimacy and quality of the studies and their significance to the decision-makers. The authors conclude by highlighting the importance and benefit of conducting an MCDA in contrast to e.g. Benefit-Cost Analysis (BCA) because the process of an MCDA is open and the decision-makers are emotionally involved in it. However, the authors found no clear relationship between legitimacy and the quality of the studies (Wenstøp and Seip, 2001).

There are numerous of other articles that review MCDA methods and approaches, e.g. a synthesisation on state-of-the-art research in comparative risk assessment (CRA), MCDA and adaptive management methods applicable in remediation and restoration projects, (e.g. Linkov et al., 2006b, Linkov et al., 2006a) and a review on the use of eco-efficiency in contaminated land management (Sorvari et al., 2009).

7.1.2 Sustainability assessments

Bello-Dambatta et al. (2009) reviews different decision support techniques and methods for decision-making and analysis when dealing with contaminated land. The paper pays special attention to AHP, which is illustrated with a case study. The aim of the case study was to find a sustainable remediation alternative for the cleanup of a former petrol filling station and repair workshop while considering hydrology and contamination type, extent and behaviour. No information is given in the paper about what the site is going to be used for in the future. Three decision alternatives for the cleanup were considered, Monitored Natural Attenuation (MNA), Enhanced Natural Attenuation (ENA) (pump and dispose) and ENA with air sparging, these were compared to each other by the use of the following sustainability criteria:

- Regulatory obligations
- Cost-effectiveness
- Technical efficacy
- Waste by-products
- Societal considerations
- Wider environment.

The pair wise comparisons of each alternative were performed by questions about how much more important or dominant one alternative were compared to another in respect to a criterion. The alternatives were also compared with respect to the goal. Both comparisons were made through expert judgment from practioners involved in the project and survey from technical literature. The comparison matrix was checked for consistency (Bello-Dambatta et al., 2009).

A Swedish example is the MCA model developed by Rosén et al. (2009). The aim of the report, written for the program Sustainable Remediation (SEPA), is to suggest an MCA model to compare remediation alternatives regarding sustainability. Rosén et al. (2009) also aims at testing the MCA model on a real case. The authors attempt has been to develop a simple-to-use and explicit model.

In an MCA evaluation, the overall objective and criteria are essential. Table 7-1 lists the sub-criteria for the criteria Ecology and Socio-cultural. The criteria Economy is handled with a CBA. Table 7-2 shows the cost and benefit posts in that CBA. For further description of how the CBA works in the process to decide between remedial alternatives for contaminated sites, see Rosen et al (2008).

Table 7-1. Sub-criteria for the criteria Ecology and Socio-cultural. Amended after Rosén et al. (2009).

Ecology	**Socio- cultural**
Land	Equity and acceptance
Ground water	Health in regard to contaminants on site
Surface water	Health in regard to remediation execution
Air	Cultural environment (landscape scene)
Sediment	Recreation and outdoor life
Use of natural resources	Land use in the surroundings
	Land use on site

Table 7-2. Main posts in the cost-benefit analysis for the criterion Economy.

Costs	Benefits
Costs for the remediation	Increased market value
Negative effects on health due to the remediation process	The net effect on market-priced goods and services
Negative effects on eco system goods and services due to the remediation process	The net effect on non-market-priced goods and services

The authors have chosen not to include any weighting on the criteria or sub-criteria. They discuss the importance of choosing criteria carefully and argue for an equal weight to all sub-criteria since they are considered equally important. They use a null-alternative to score against hence measuring the chosen remediation alternatives changes/effects in a positive or negative direction. For a possible positive change towards the null-alternative, a remediation alternative score +1 and for a probable positive change it scores +2 on the evaluated sub-criterion. The negative changes are handled in the same way with scores from -1 to -2. This is performed for all sub-criteria.

The MCA working process developed by Rosén et al. (2009) follows a step-by-step working chart; Figure 7-1. The authors use the concept of weak and strong sustainability, often used by economists, by calculating a sustainability index for the different remediation alternatives. The result show whether the alternative is heading towards weak or strong sustainability.

To explain the different forms of sustainability the economists use the concept of capital; natural capital, manmade capital and human capital. In the case of weak sustainability, the sum of all capitals is constant over time. This can be the case if compensation between capitals is allowed. If no compensation is allowed and no individual capital decline over time then strong sustainability is achieved (Rosén et al., 2009).

Rosén et al. (2009) use two MCA techniques; a non-compensatory method for sorting out all alternative remediation techniques which do not head towards strong sustainability and the linear additive model to identify the most sustainable alternative either among alternatives heading towards strong sustainability or among those heading towards weak sustainability.

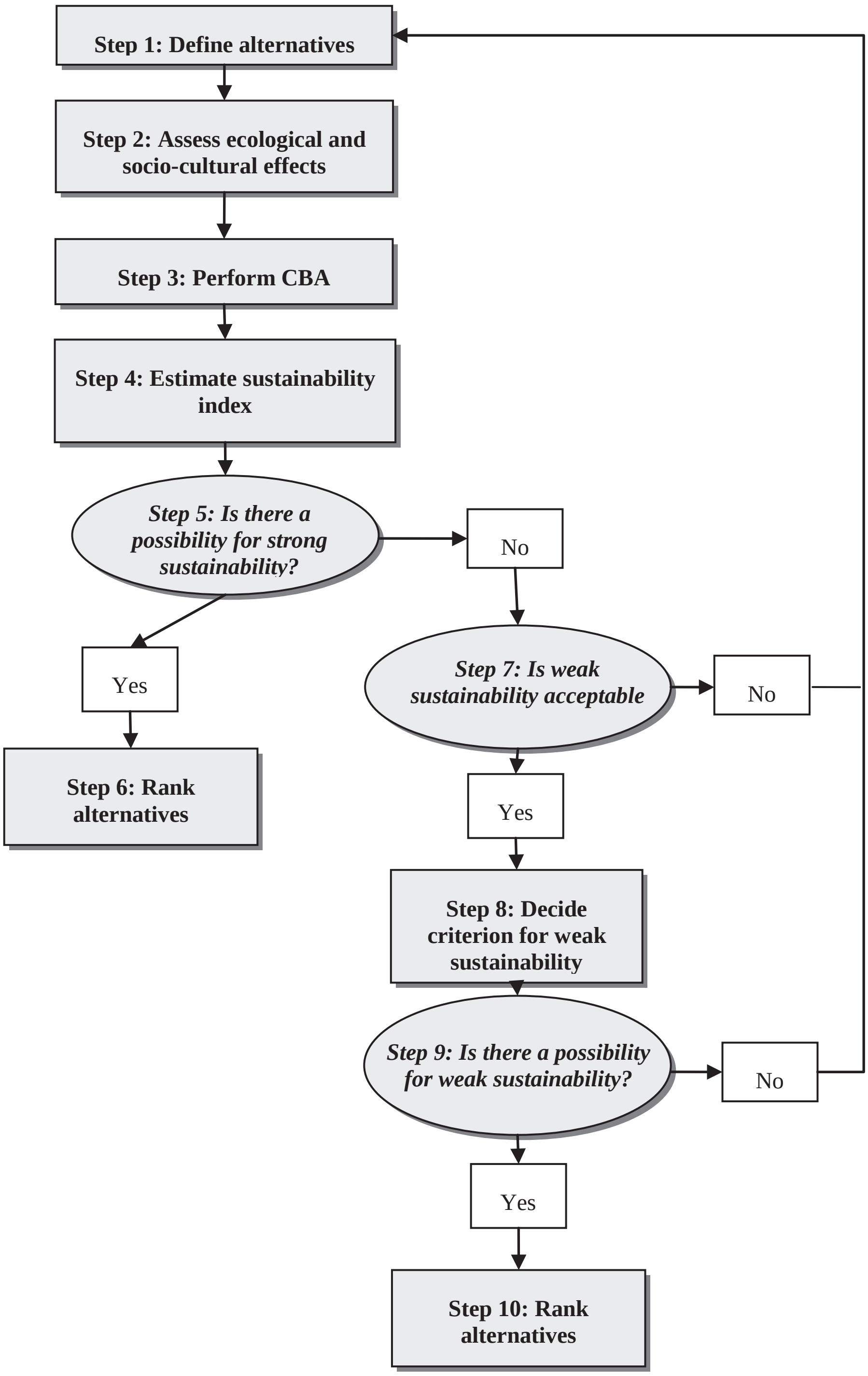


Figure 7-1. Step-by-step working chart for ranking remediation alternatives, after Rosen et al. (2009).

Rosén et al. (2009) emphasize that the positive or negative changes, to the Economic, Ecologic and Socio-cultural criteria, that emerge from implementing a remediation alternatives reveals if the society heads towards strong or weak sustainable development. An alternative heading towards weak sustainability has negative impact on one or several sub-criteria. An alternative heading towards strong sustainability has no impact, or positive impact, on all sub-criteria.

The case study presented in the report is from a small community, Robertsfors, in the northern part of Sweden. The contaminated property is a former impregnation industry. Remediation has already been executed on the property so the authors are doing an MCA *ex post*. The remedial alternatives compared in this case study are alternatives that were considered during the remediation selection process. The persons that scored the alternatives against the sub-criteria were persons involved in the project, i.e. consultants and officials from the municipality. The authors emphasize that it is preferred that the public is involved when evaluating the socio-cultural criteria, through focus group meetings if the method is to be used in a real case (Rosén et al., 2009).

Ritchey (2008) developed, with funding from the Program Sustainable Remediation (SEPA), a computer-aided instrument, based on AHP, to support risk valuation in remediation. The work was carried out by the Swedish Defence Research Agency (FOI). The development of the instrument and gathering criteria were conducted through work-shop seminars with experts in the field of remediation.

The aim with the instrument was to give better structure, consistency, and traceability of risk valuations for the remediation of contaminated sites. The instrument was tested on a real case in Sweden where the remediation project was concerned with decontamination of a closed saw-mill in Vackelsång, in the Swedish municipality Tingsryd. The AHP instrument was compiled of three criteria followed by two levels of sub-criteria, see Table 7-3 for criteria and first-level of sub-criteria.

Table 7-3. Criteria and first-level sub-criteria used during assessment of the saw-mill in Tingsryd (Ritchey, 2008).

Ecological	**Economic**	**Socio-cultural**
Risks in a long perspective, and.	Investment costs, and	Public welfare
Risks during remediation process	Costs for maintenance	Achievement of political goals
Use of resource regionally and globally	Maximised revenue	Acceptance
		Minimising risk responsibility

The instrument used in Ritchey (2008) was developed in the software Expert Choice which originally was developed by the creator of AHP, Thomas Saaty. All three alternatives were first valued against the lowest level of sub-criteria and after that were the lowest level criteria valued against the level next above it. Further valuing was made in the hierarchy structure upwards. The alternatives are valued pair- wise. No conduction of a sensitivity analysis is described in the report.

Postle et al. (1999) developed a procedure described in a handbook, a technical report, to be used for comparing remediation techniques at a given site and to determine the significance of identified criteria before, during, and after a remediation process when managing contaminated land. The handbook is a guidance document for a transparent and consistent assessment of the costs and benefits for remediation of land contaminations. The MCA method used for that context is the linear additive method. This procedure was developed to enable and highlight the significance of impacts and comparison between different remediation techniques. Postle et al. (1999) divide the assessment in five main steps to be followed in order from step one to five, see fig 7-2. The steps include the following parts.

- *Step one* is a screening stage where the characteristics of the contamination problem is examined. Also, this step is where it is determined what could be appropriate solutions for the specific sites and hence further assessment requirements are determined.

- *Step two* is a qualitative assessment of the potential impacts of the remedial alternatives and a simple CEA. A qualitative appraisal includes an identification of impacts with respect to the following criteria:

- Human health and safety
- Environment
- Land use
- Third party stakeholder concern

- *Step three* includes an MCA with a CEA applied for the cases where there is a complex range of issues and a greater choice of acceptable remediation solutions.

- *Step four* includes monetary valuation, when possible. The sum of costs and benefits are calculated in a CBA which will reveal if benefits overweight costs.

- *Step five* involves the final step which is a sensitivity analysis followed by a ranking of the preferred remedial alternative and the final decision.

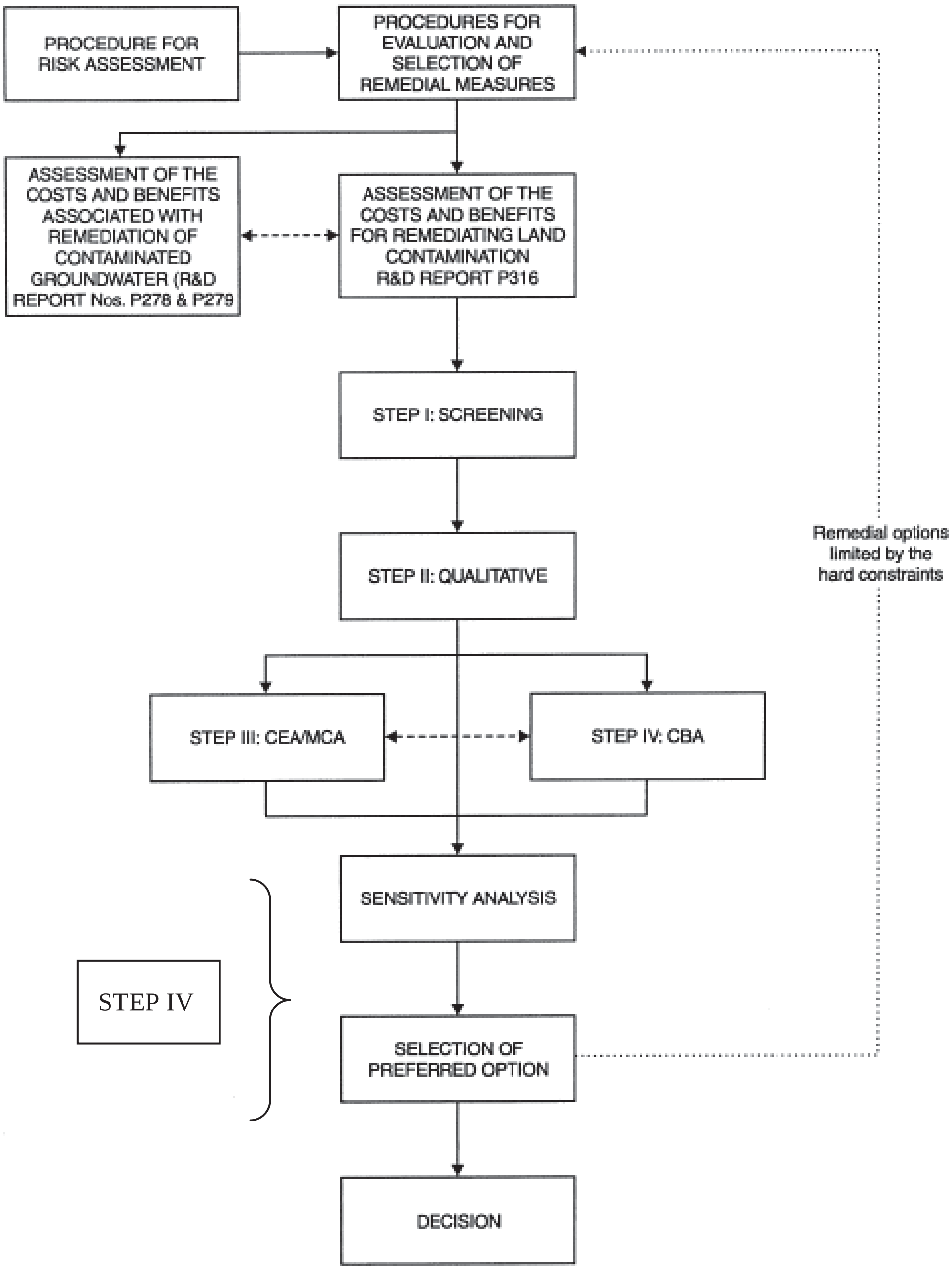


Figure 7-2. Interrelationship between steps in the assessment of costs and benefits for remediation contaminated land, after Postle et al. (1999).

For first-level sub-criteria used in Postle et al. (1999), see appendix 2. It is further described, in the report, how the weights should be decided with respect to the experts and stakeholder's point of view (Postle et al., 1999).

Harbottle et al. (2005, 2006, 2007 2008a, 2008b) have written a series of articles, which in some aspects deal with the same overall objective. They address the sustainability of land remediation looking at both an overall analysis and an impact assessment. The overall analysis was performed with an MCA method and the impact assessment with an LCA. However, the different papers concentrate on a varying set of remedial techniques as well as sites. The authors revise the financial analysis as well as the MCA, especially concerning the sub-criteria, from paper to paper.

The first method to assess impacts is a continuation of the MCA method described in Postle et al (1999), see p. 67. Harbottle et al. (2005, 2006, 2007, 2008b) have amended and expanded the original method since the objectives in Postle (1999) primarily dealt with finding the optimal remedial alternative at a specific site. Harbottle et al. (2005, 2006, 2007, 2008a and 2008b) seeks to answer how sustainable a remediation technique really is, in some papers including the nil-alternative, by comparing various techniques used at different sites. The MCA technique used, in all articles, is the linear additive method. The overall MCA scores were combined with simple financial costs to give a final cost-effectiveness score. The second method, LCA, was used to assess environmental impacts in Harbottle et al. (2008a).

Harbottle el al. (2005, 2006, 2007, 2008a, 2008b) uses five assessment criteria to assess the overall objective, sustainability of the remediation techniques or technical sustainability. These criteria are (1) future benefits must exceed costs of remediation, (2) overall environmental impact of the process is less than if the land was left untreated, (3) the environmental impact of the remediation alternative must be minimal and measurable, (4) one must take into account the inter-generational risk as a part of the decision-making and (5) the stakeholders need to be engaged in the decision-making process, see Table 7-4.

The fifth criterion is excluded in Harbottle et al. (2007, 2008a, 2008b), however it is included in Harbottle et al. (2005, 2006) but not assessed. In Harbottle et al. (2006), a discussion is included about the importance of stakeholders' views.

Table 7-4. Overall objective and criteria assessed in Harbottle et al. (2005, 2006, 2007, 2008a, 2008b).

Overall objective	**Technical sustainability**				
Assessment	1	2	3	4	5
Criteria	Future benefits must exceed costs of remediation	Overall environmental impact of the process is less than if the land was left untreated	The environmental impact of the remediation alternative must be minimal and measurable	One must take into account the inter-generational risk as a part of the decision-making	The stakeholders need to be engaged in the decision-making process
Assessment method	MCA	LCA	LCA	LCA	Not assessed or excluded

MCA is used to assess criterion one, the overall benefits versus the costs. Criterions two to four are assessed with the second method, LCA. This analysis is able to assess the criteria more individually. Large amount of information from the LCA is included in the MCA. For further reading about the usefulness of performing a LCA, to evaluate remediation alternatives, see Suér et al. (2004).

All papers are based on the same set of assessment criteria (four or five) outlining the view of sustainability assessment for technical and environmental aspects of contaminated land remediation.

Assessment criterion one, Table 7-4, can be viewed as an overall objective for the MCA, hence resulting in the use of five criteria for the MCA, Table 7-5. These five criteria are (1) human health and safety, (2) local environment, (3) third party/stake-holder concern, (4) site use and (5) global environment, These five criteria are further divided in 18 sub-criteria, see Table 7-5. The 18 sub-criteria are scored and weighted in the MCA for an overall impact assessment of the remediation.

Table 7-5. Criteria and sub-criteria assessed in Harbottle et al. (2005, 2006, 2007, 2008a, 2008b).

Criteria	**sub-criteria**
Human health and safety	Risks to site users Risk to public
Local environment	Surface water quality Surface water quantity Ground water quality Ground water quantity Air quality (pollution) Quality/structure of soil Habitat/ecology
Third party/stake-holder concern	Third party/stakeholder confidence Third party/stakeholder acceptability
Site use	Duration of remediation Impact on landscape Site use Surrounding land use
Global environment	Air-quality (green-house gas) Use of natural resources Non-recyclable waste

Data input to the MCA and the LCA were retrieved through a number of different calculating programs and table numbers, as well as calculated costs and change in estimated land value for the calculation of financial costs. Scoring and weighting on the sub-criteria were then preformed in a semi-subjective manner with data and available evidence used to justify values. No aggregations of scores were made of the LCA result because of the vast amount of data retrieved. Scores are given to each sub-criterion both on-site and off-site, during and after remediation. A weighted sub-criteria score was calculated for each technique followed by a total score for the technique.

The analysis in Harbottle et al. (2006, 2007, 2008a, 2008b) is a revised and expanded form of the one elaborated in the Harbottle et al. (2005). Harbottle et al. (2007) treats the cost-effectiveness differently than Harbottle et al. (2005, 2006) to avoid that a technique gets erroneously ranked. In Harbottle et al. (2005, 2006), the financial costs are treated as an additional scoring category.

The aim of the case study in Harbottle et al. (2005, 2006) is to compare the predicted effects if a long-term contaminated site is left untreated with the effects if two different remediation techniques, one in situ technique and one off-site disposal are used. The site is a mixed industrial/commercial/residential area in England with former industrial activity on the site which in the future is planned to be a residential area.

Harbottle et al. (2007) is basically the same as Harbottle et al. (2005, 2006) but with the comparison between the two remediation techniques excluding the nil-alternative. Some changes have also been made to the cost-effectiveness analysis as stated earlier.

Harbottle et al. (2008a, 2008b) analyses five different techniques at five different sites in a case study application. They were chosen based on one criterion: what remediation technique that had been used on the site. The sites were former industrial sites. This article is divided in two parts with the first dealing with the overall analysis, MCA, and the second with the detailed impact assessment (DIA).The second part presents and addresses the remaining three sustainability criteria set out in the first part. The discussion in the second part brings together findings from both parts.

Uncertainties were dealt with through a sensitivity analysis that determined the sensitivity of the remediation technique by varying both scores and weights (Harbottle et al., 2008a, Harbottle et al., 2008b, Harbottle et al., 2007, Harbottle et al., 2006, Harbottle et al., 2005).

7.1.3 **Soil remediation**

A quite recent and comprehensive paper about the choice between risk management (i.e. remediation alternatives) alternatives was published by Sorvari and Seppälä (2010). In the project PIRRE funded by the Ministry of Environment and project partner within the Finish Environmental Cluster Research Program has the authors developed their own Decision Support Software Tool to prioritize risk management options for contaminated land.

The tool is based on the Dutch Risk Environment Cost (REC) system. Sorvari and Seppälä (2010) chose to build their tool on MAVT as the theoretical basis. First, they constructed a value tree to structure the decision problem and criteria. The criteria were further divided in 11 first level sub-criteria and four second level sub-criteria, see Figure 7-3.

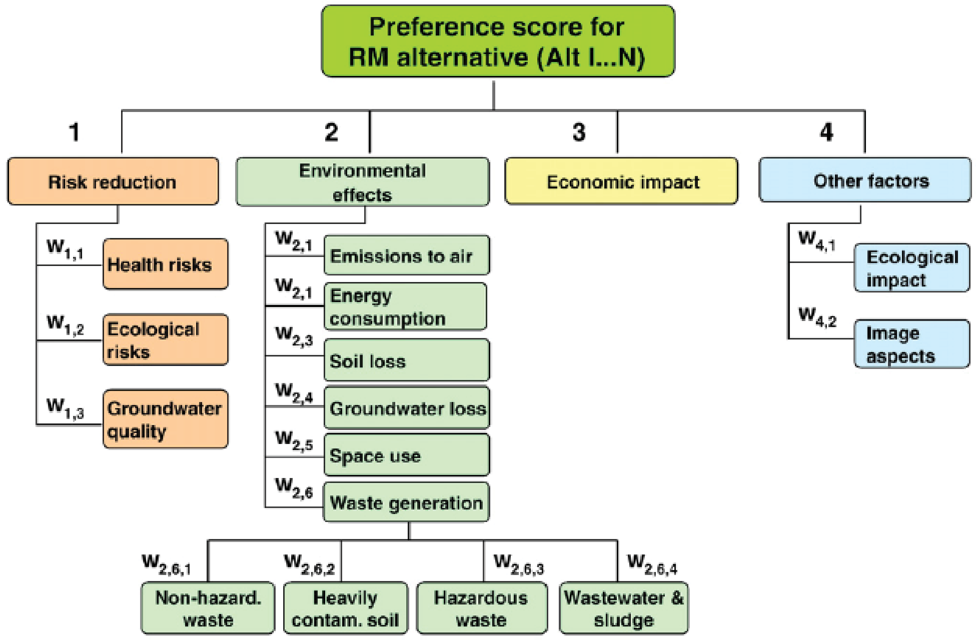


Figure 7-3. Hierarchy of criteria for evaluation of remediation management alternatives (Sorvari and Seppälä., 2010).

The Risk Management (RM) alternatives are defined on the basis of criteria and the measurement level of a criterion is expressed in value scores. Each criterion can be handled separately in MAVT and the preference order of the RM alternatives within each criterion was calculated using an additive value function. The total preference score for each RM alternative is a combination of sub-criteria for each criterion. To test the model the authors used two case studies, one shooting range and one gasoline station. The value scores for first and second level sub-criteria for different RM alternatives were gathered from other remediation projects and by interviewing several experts. A series of calculations with different instruments and other surveys resulted in numerical values for all sub-criteria.

For the weighting of criteria the authors first put together a background material which was reviewed by an expert group and later revised to finally be handed out at a stakeholder seminar. The stakeholders then valued the criteria and all levels sub-criteria. They used the weighting based on ratio estimating technique. They also studied the weighting by doing pair wise comparisons and a sensitivity analysis (Sorvari and Seppälä, 2010).

Since the importance of stakeholder involvement is well founded in the literature the decision for contaminated site management has to take into account the inputs from stakeholders with various objectives and priorities. Jianbing Li et al. (2010) concentrates on the uncertainties about stakeholders ranking and weighting of alternatives and criteria. The approach is similar to and an extension of the work of Promentilla et al. (2008). Jianbing Li et al. (2010) develop the Fuzzy Multi-Criteria Decision Analysis approach (FMCDA) for evaluating and ranking remediation alternatives by considering stakeholders preferences and uncertainties. The authors present a case study about a property in northern British Columbia, Canada. The site was contaminated with Hydrocarbons. Six remediation alternatives are presented and evaluated against 10 criteria. Each criterion was divided in five fuzzy sets and the membership function of each set was constructed based on results from a questionnaire survey to stakeholders. Stakeholders were also asked about their opinion on the importance of criteria. The FMCDA were compared to more conventional MCDA techniques e.g. SAW and TOPSIS. The result from the FMCDA was found to be more acceptable than the conventional MCDA approaches since it incorporated stakeholders' uncertainties in their opinions into the decision analysis framework.

Critto and Agostini (2009) aim to present scientific indices created within the decision support system for rehabilitation of contaminated land called DESYRE. DESYRE is a software program which helps in decision making for clean-up of mega sites. Carlon et al. (2007) gives a detailed description of the software.

DESYRE is a spatial decision support system and produces a map with different thematic layers, e.g. land use, technological application and so on. The program is divided in six modules which individually represent a specific aspect of the remediation process. The modules are Socio-economic, Characterization, Risk assessment (pre and post), Technological and Decision, see Figure 7-4. The produced indices from the other modules are delivered to the decision model. The choice of remediation technique/s is performed by the use of an MCA method inside the technological module. The technological module with the MCA method is further described in Critto et al. (2006).

The decision module provides a description of alternative rehabilitation scenarios where a scenario is a solution for the rehabilitation and includes land use, socio- economic benefits, the remediation costs, the time span, the environmental impacts, the technology/s set and the residual risk (Critto and Agostini, 2009).

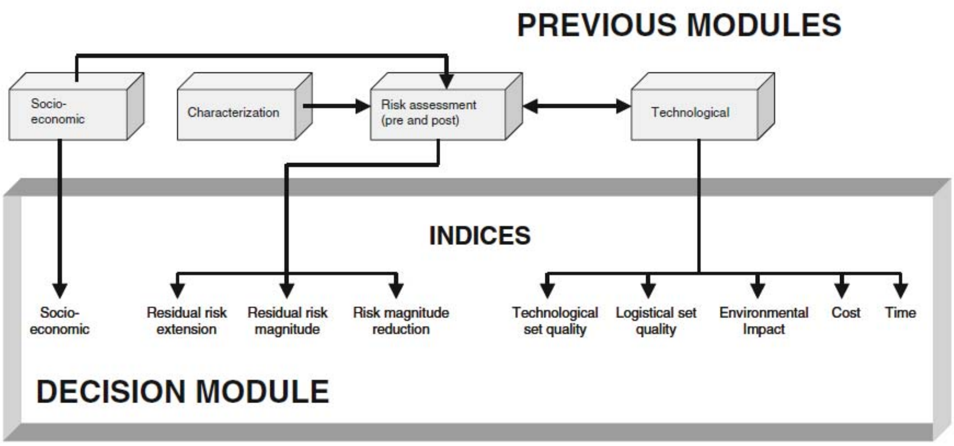


Figure 7-4. Modules and indices within the decision program DESYRE, from Critto and Agostini (2009).

Balasubramaniam et al. (2007) focus on both how many and what kind of participants should be involved in the decision process of choosing remediation alternative for petroleum contaminated land. The investigation about participants was done with a build up of three different impact scenarios of contamination of petroleum. The scenarios build on a real case study from the Environmental Agency. The participants were experts, stakeholders and the public and they were asked questions about the importance of criteria (weighting) through a questionnaire. The utility of the weighting program SWING was also evaluated through the process with the scenarios. Some of the original criteria were used and some added. The final set of criteria was:

- Risk to health of site users
- Risk to health of general public
- Surface water quality
- Habitats and ecology
- Financial impact on local residents

In the questionnaires given to the participants, the criteria scores were held constant so the effect of the different weight sets would be transparent. The methods used when ranking the remediation alternatives were weighted summation (MCA) and the outranking method ELECTRE III. The conclusion of the study is that it is important to involve a mixture of stakeholders, experts and the public with an emphasis on the public. The number of participants should be limited by participatory and weighting method. A conclusion about the MCA method and the outranking method is that it is good to use several methods.

Herman et al. (2007) presents an analytical tool called COMPLIMENT. This tool integrates parts of LCA (data collection), MCA (weighting and aggregation of weights through AHP) and Environmental Performance Indicators (EPI). A case study is presented to illustrate the use of the new combination of tools for a realistic case. The case is about a soda pulp industry in Thailand. The industry pollutes through emissions to water and air and an evaluation of the industry's environmental impact was evaluated. The authors divide the weights in a local, a regional and a global perspective to take into account the geographical scale. An impact in the global perspective is e.g. global warming compared to the local perspective where issues like human health and ozone precursors dominated. According to the authors, one of the strengths of COMPLIMENT is that it is a "cradle-to-gate" approach taking care of the whole assessment process and they conclude that by combining the best parts of the three methods the following can be achieved with the method:

- Completeness through an inclusion of the parts of the production chain that are outside the boundaries of the industry itself.
- Results in one indicator, making the results easy to interpret for policy purposes.
- Uses readily available information.

Herman et al. (2007) perform a sensitivity analysis of the different perspectives; local, regional and global.

According to Scholz and Schnabel (2006) is the method they present, a general, consistent and transparent method. The method is a tool to be used in decision-making among remediation alternatives. They use an MCDA method based on utility functions (MAUT) which take into account uncertainties with help of probability density functions representing contamination for all site coordinates. The following criteria were used in the study Scholz and Schnabel (2006):

- Human health impact
- Remediation costs
- Long-term productivity of soil
- Market value of land after action

Promentilla (2006) evaluates the Analytic Network Process (ANP), a form of AHP as a decision aid at the planning stages of site remediation. ANP is tested with an example of an evaluation of feasible remedial measures of a contaminated site caused by an uncontrolled landfill. Promentilla et al. (2008) states that it seems to be inherent to deal with fuzziness or uncertainty in judgments during a pair-wise comparison process and hence introduce a fuzzy set to the ANP. The fuzzy ANP is an extension of the ANP which captures the vagueness and fuzziness during value judgement elicitation in the remedial evaluation process. (Promentilla et al., 2008, Promentilla et al., 2006).

Janikowski et al. (2000) use AHP on a case in the Katowice District in Poland. A set of 12 possible remediation alternatives is presented and evaluated against seven criteria. The following criteria were used:

- Time to complete clean-up
- Possibility of multi-functional use after application
- Environmental cost
- Social acceptability
- Effectiveness in removing a wide range of heavy metal concentrations
- Long-term effectiveness
- Cost effectiveness

The importance of one alternative over another was made by an expert group of three experts in the fields of ecology, agriculture and environmental policy. The authors conclude that the MCA method can be applied to several different activity and technology evaluation and it allows for consideration of numerous perspectives and interest of particular stakeholders.

Bonano et al. (2000) developed a framework which integrates risk assessment and decision analysis for evaluating and selecting preferred remediation alternatives at a contaminated site. It is through stakeholder inputs, through the entire process, that the authors get in-data to the MCDA model and employs those inputs to combine the results of multiple risk assessments to arrive at a total impact for each remediation alternative. The authors have identified the following criteria as major risks or impacts:

- Human health and safety
- Environmental protection
- Life-cycle costs
- Socio-economics
- Cultural

- Archaeological and historical resources
- Programmatic assumptions

The overall objective of this study is to maximise benefits of remediation. The criteria above are further sub-divided in first and second-level criteria (Bonano et al., 2000).

To demonstrate a decision model for remediation decisions, i.e. to choose remediation technique, Kruber and Schoene (1998) chose a case study site in Bergen, Norway. The site was a large waste-disposal site that leaked contaminants to the ground and surface water. When the case study was conducted the waste site was still in operation and no future land use was decided. Four criteria were chosen for the decision:

- Financial criteria
- Economic effects
- Balance of volume of waste disposal and
- Environmental criteria

In addition to these, sub-criteria were also depicted. Four scenarios with different outcomes for the running of the waste disposal were decided, ranging from complete closure to a move to another site. A calculation of the total utility of each remediation scenario was used as the decision model. Uncertainty was considered by Kruber and Schoene by calculating the distributions of the functionally dependent variables (e.g. criteria and the total utility) by Monte Carlo simulation (Kruber and Schoene, 1998).

7.1.4 Sediment management

Alvarez-Guerra et al. (2009) addresses the problems of prioritization in sediment management. It is possible to have, in the same site, different sediment qualities and also different anthropogenic pressure which can be dealt with by making differentiated management units for different parts of the site. An MCA can be used as a decision support when prioritising between sediment management of different management units in one site. For the management of contaminated sediments Alvarez-Guerra et al. (2009) states that the most common way to assess sediment quality is by using the Multiple Line of Evidence (LOE).

When developing several LOEs the Sediment Quality Triad is the most commonly used approach. The triad approach requires evidence in three components, sediment chemistry, laboratory toxicity and resident community alterations (the benthic in the fauna). The outcomes of all such lines of evidence are criteria in the MCA. The authors state the importance of complementary criteria to the LOEs, e.g. technical, economic, social and environmental criteria for the assessment of both the need of management and the management alternative. The case study presented is based on a real case. Several MCA techniques: weighted summation, two outranking methods and AHP, have been used to evaluate how they perform against each other and to establish uncertainties with the different techniques. The authors propose that regardless of technique used to determine an alternative; a sensitivity analysis should be performed using different distributions of weights (Alvarez-Guerra et al., 2009).

Yatsalo et al. (2007) use previous investigations on two case studies, Cocheco River Superfund site and New York/New Jersey Harbour, originally reported in Rogers (2004) and Kiker (2007). The aim of the paper by Yatsalo et al. (2007) is to illustrate the application of three different MCDA methods on these two real cases. The methods used are MAVT (SMART), one outranking method (PROMETHEE) and AHP. Both cases handle the problem of contaminated sediments that needs to be removed due to (1) economic redevelopment of Dover and (2) to maintain a navigable channel for federal navigation. At the Cocheco River, four alternatives are presented

- Wetland restoration
- Cement manufacture
- Upland disposal cell
- Cement stabilization in flowable fill

and the following four criteria have been used in the evaluation:

- Cost
- Environmental quality
- Impact on ecology
- Impact on human habitat

For the weighting process there were originally four scenarios presented to the group of experts and stakeholders. Only two of these scenarios are accounted for in the paper.

For the NY/NJ harbour eight alternatives are presented including the nil-alternative, and the following seven criteria were proposed:

- Impacted area/capacity
- Magnitude of ecological hazard quotient
- Ecological pathways
- Human pathways
- Magnitude of cancer risk
- Ratio of fish contaminant of concern
- Risk level and cost

For this case, three scenarios were presented in the weighting process. The weighting was done by stakeholders and experts. Non NY experts were given a SWING weight survey to calculate the weights. Stakeholders and experts were also involved in structuring the MCDA problems and developing the performance tables. The authors come to the conclusion that the different MCDA methods rank the alternatives similarly but it is suggested to use more than one method to get a robust decision material.

Prato (2003) demonstrates the use of multiple attribute evaluation in ecosystem management of the Missouri River system by using two evaluation methods: concordance-discordance analysis and utility maximization. Prato uses the following criteria in the evaluation of five management options:

- Flood control
- Hydropower
- Recreation
- Missouri river navigation
- Water supply
- Fish and wildlife (incl. eight first-level sub-criteria)
- Interior drainage
- Groundwater
- Historic properties

Prato (2003) conclude the importance of valuable input from stakeholders and that the method they used could, in a traceable manner, incorporate stakeholder inputs.

8 Other applications

A whole field of research concentrates its effort towards measuring and evaluating the sustainable performance in redevelopment projects of former Brownfield areas with the use of assessment tools, e.g. MCDA and CBA (e.g. Schrenk, 2002, Wedding and Crawford-Brown, 2007, Bleicher and Gross, 2010, Schädler et al., 2010, Ding, 2005, Nijkamp et al., 2002).

In close connection to, and sometimes part of, a redevelopment of Brownfield is building-and civil engineering works. ISO CD 21929-2 (2010) is an ISO-standard covering a framework for the development of sustainability indicators for civil engineering works. The standard is under development and a part of a series of standards covering the economic, ecologic and social aspects of building-and civil engineering work as well as a methodological basis. Standard 21929-2 gives no guidelines to weighting of indicators or what method should be chosen for aggregation of assessment results.

Other applications of MCDA, not directly connected to remediation but which shows how MCDA can be used, are in fields of: decisions on waste disposal sites (Bollinger and Pictet, 2008), after use plans for urban quarries (Kaliampakos et al., 1999), to find a suitable site for the location of a sanitary landfill (Ramjeawon and Beerachee, 2008) and investigations on how to evaluate sites contaminated with radio nuclear waste (Grebenkov and Yakushau, 2007) .

Several publications, reviewed in this report, use more than one MCDA method when evaluating remediation alternatives to test the robustness of the methods. A paper that solely focuses on that subject is Cloquell-Ballester et al. (2007). Another paper by the same authors Cloquell-Ballester et al. (2006) focus on how to validate and improve indicators used in environmental and social impact quantitative assessment.

8.1 Decision support software tools

There are some tools available on the market to evaluate the sustainability of remediation alternatives, e.g. SRT, GoldSET©, SiteWise™ and VHGFM. These are further described in the section below.

The Sustainable Remediation Tool (SRT) is developed by the U.S. Air Force Center for Engineering and the Environment and their partners to incorporate sustainability in Air Force remediation practices. SRT aims at giving aid in the selection of remediation technology and as an optimization tool for existing remediation projects. It is possible to choose from a set of four techniques within the program. Two are for soil remediation and two are for remediation of water. The approach within SRT can be a tier 1 approach or a tier 2 approach which is site specific. The outcomes of the calculations are sustainability metrics associated to soil and groundwater remediation. The metrics are carbon dioxide emissions to the atmosphere, nitrogen oxides, sulphur oxides, particulate matter (PM10), total energy consumed, technology cost, safety/accident risk and change in natural resource services (Becvar et al., 2009). For instructions to a free download of SRT see Appendix 4.

SiteWise™ is an American excel-based decision-support tool, mainly focusing on the environmental impacts of remediation alternatives. The tool is developed in cooperation between U.S Navy, U.S Army Corps of Engineers (USACE) and Battelle. It requires a wide range of in-put data to the different phases of a remediation to calculate and display results in the categories shown in Figure 7-5. The result is an environmental footprint including a calculation of the life-cycle environmental footprint of the material used during remediation.

The phases of remediation which are accounted for in the calculation are: remedial investigation, remedial action construction and operations and long-term monitoring. The in-put data required in these phases are Consumables, Transportation-Personnel, Transportation-Equipment, Equipment Use and Misc, and Residual Handling (Bhargava et al., 2009, Darlington et al., 2009). For instructions to the webpage where SiteWise can be down-loaded see Appendix 4.

Remedial Alternative	GHG	Total energy Used	Water Consumption	NO_x	SO_x	PM_{10}	Accident Risk Fatality	Accident Risk Injury
	metric ton	MMBTU	gallons	metric ton	metric ton	metric ton		
Remedial Alternative								

Figure 7-5. Assessment result table from SiteWise displaying each alternatives performance for each category.

The usefulness of SRT and SiteWise™ in remediation projects in Sweden have been investigated by Ferdos (2011) by applications on two case study sites.

GoldSET© (Golder Sustainability Evaluation Tool) is decision-support tool developed by Golder Associates for their projects in oil and gas, public sector, waste water management, transportation, mining, remediation and construction. The tool evaluates strengths and weaknesses by comparing management alternatives against each other, through an MCA, by using quantitative or qualitative indicators representing the environment, the social and economical and technical dimensions. There are 38 indicators to choose from. The evaluation results in a rating of alternative based on the performance of each alternative against the indicators. The outcome of each alternative and a comparison between the alternatives is visualised in a diamond diagram, see Figure 7-6. The alternative with the most symmetrical diamond is the most sustainable among the compared alternatives. For instructions to the webpage where GoldSET can be down-loaded see Appendix 4.

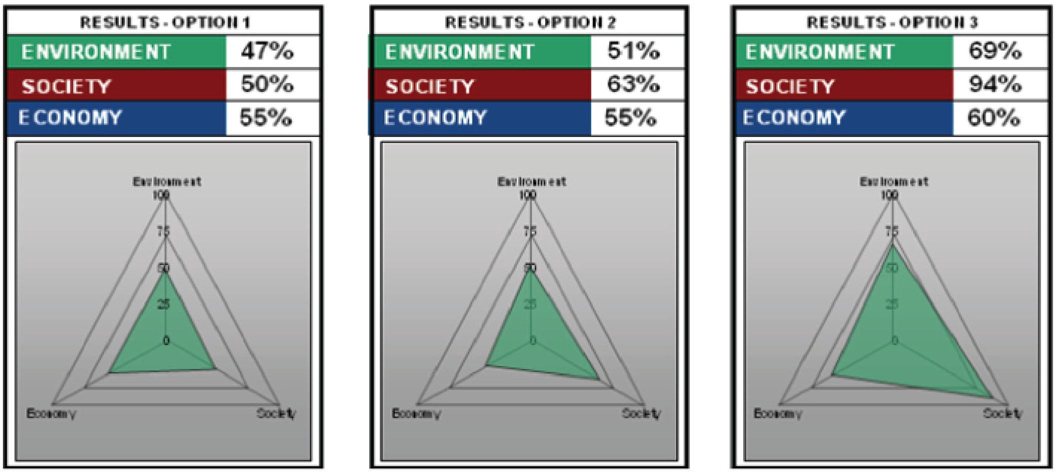


Figure 7-6. Assessment results visualised in diamond diagrams, of three remediation alternatives from GoldSET, (GoldSET, 2010).

VHGFM is a Swedish excel-based decision-support tool used when comparing a number of remediation alternatives against each other. The tool mainly calculates the green house gas emissions from remediation alternatives in *CO_2- equivalents*. It is developed in cooperation between Swedish Geotechnical Association (SGF), SEPA, The Development Fund of The Swedish Construction Industry (SBUF), WSP Environmental, MB Envirotek, NCC and SAKAB. The following remediation methods are possible to evaluate within VHGFM:

- In situ biological aerobe degradation
- On-site biological degradation
- Off-site biological degradation
- Soil washing
- Thermal desorption
- Landfill
- Barriers on-site number of remediation alternatives can be compared at the same time and

The usefulness of VHGFM for Swedish conditions have been investigated by (Almqvist et al., 2011).

9 Discussion and conclusions

There is a common understanding among the environmental experts that a holistic environmental consideration must be taken while “cleaning” land from contamination. It would be a bad act, to again pollute the living environment for humans and other species while trying to do a good act. Remediation has traditionally been viewed as a sustainable act in itself. However, during the last few years a discussion has emerged where this is being questioned since the act itself could contribute negatively to the environment and the society (Vegter, 2002).

Therefore, it is important to expand the evaluation from a local environmental impact assessment of remediation projects to an assessment of impacts on a higher, more holistic level, where the society, economy and environment is assessed together (Smith, 2010). The challenge with the large numbers of contaminated sites can create an opportunity to develop cooperation between disciplines, e.g. economists, social sciences, statisticians, risk analysts and environmental specialists (Kasemir et al., 2003).

One of the key players in remediation of properties are construction companies, which have an opportunity to contribute to the clean-up of land but at the same time, have to handle large project risks connected to the remediation process. These risks are present throughout the whole project, from acquiring land until the residential area is built (Rosén and Wikström, 2005; Reference group meeting, 2010). Important parts of managing risks is to be aware of their presence in advance and value if measures are needed to reduce the identified risks, i.e. risk identification and valuation. These risks should also be considered in a more holistic sustainability assessment. How to incorporate them in the further development of the MCDA-tool as a tool for sustainability assessment of remediation prior to construction is still work in progress.

The most commonly used remediation technique in remediation both prior to construction and in regular remediation projects is excavation. Excavation can be performed in different ways and is often an effective measure considering the time-limits that construction companies work under. Excavation performed in a gentle way, together with measures to reduce transports, e.g. sieving and soil washing, enables the negative environmental impacts to be reduced. Further, a correct classification of the contaminated soil is a prerequisite for minimising the negative environmental impacts due to transportation.

MCDA is one of several assessment tools that is able to handle both project risks for e.g. construction companies and at the same time take into account the wider perspective of remediation, i.e. the sustainability of different remediation alternatives (Smith, 2010; Ness et al., 2007).

MCDA methods have previously been used for evaluating remediation alternatives, as shown in this literature review. The main application has been to evaluate the environmental impacts and to some extent the economic impacts, even though it is mainly the costs that have been taken into consideration. The societal aspects are not widely considered, i.e. MCDA has not been widely used as a decision support for evaluation of sustainability of remediation alternatives with regard to all three elements of sustainability, as also has been stated by Harbottle et al. (2008b).

Computer-based Decision Support Tools are available at the market today, e.g. SiteWise, SRT and GoldSET. The first two mainly handle the contributions of Green House Gases from remediation projects while GoldSET aims at evaluating the sustainability of remediation alternatives based on the three elements of sustainability; ecology, economy and socio-culture.

There are obvious but still important aspects to highlight when constructing an MCDA model. The MCDA model should: (1) be based on an MCDA method (e.g. a compensatory, non-compensatory or outranking method or a combination of those) which is able to handle the decision problem at hand (2) have a structure of criteria that reflect the overall objective in the best way to facilitate elicitation of scores as well as weights, and (3) consider uncertainties in all parts of the model, from construction of hierarchy to performance evaluation.

Conclusions

- Sustainable development and hence sustainable remediation is in great focus among remediation experts working with remediation projects as well as among organisations e.g. USEPA, SuRF and SuRF-UK.
- There is still not a single accepted framework on how to incorporate the assessment of sustainability in remediation projects and hence not a single accepted method on how to evaluate the sustainability of remediation projects. Methods that have been used for these kinds of assessments are e.g. MCDA-methods, LCA and CBA.
- MCDA have been used in several applications for evaluation of remediation alternatives in soil and sediment as well as in other adjacent areas and works as a structured transparent way of communicating the choice of e.g. a method or a solution.
- Stakeholder involvement in the process of conducting MCDA in remediation projects is considered very important even though not often considered. The involvement of stakeholders, both interest groups and the community asserts that the decision has a good foundation among those affected by it.
- There is a common understanding that it is of great importance to handle the uncertainties in an MCDA. By several sources this is handled by a sensitivity analysis. A sensitivity analysis can be made both with regard to input data such as scores, weights and structure but also with respect to different MCDA methods (e.g. linear additive model, AHP and outranking methods).
- Construction companies are a key player in the remediation business since they buy contaminated land for redevelopment purposes. There are large project risks with these purchases in all phases of the building process, e.g. an uncertain contamination situation, conjuncture and communication with authorities. These should be incorporated in a sustainability appraisal tool for the building process.

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Appendix

Appendix 1: Sustainability indicators from Surf-UK (2010)

Sustainable Remediation Indicators

SuRF SUSTAINABLE REMEDIATION FORUM UK

Environmental Indicators

ELEMENT	CATEGORY	ISSUES THAT INDICATORS MIGHT NEED TO CONSIDERED
Environmental 1	**Impacts on air**	Emissions that may affect climate change or air quality, such as greenhouse gases (e.g. CO_2, CH_4, N_2O), NO_X, SO_X, particulates (especially PM5 and PM10), O_3, VOCs, ozone-depleting substances, etc. *(Note: Does not include any odorous effects, bioaerosols, allergens or dust, as these are included in 'Social 3: Impacts on neighbourhoods or regions'.)*
Environmental 2	**Impacts on soil and ground conditions**	Changes in physical, chemical, biological soil condition that affects the functions or services provided by soils. May include soil quality (chemistry), water filtration and purification processes, soil structure and/or organic matter content or quality; erosion and soil stability, geotechnical properties, compaction and other damage to soil structure affecting stability, drainage, or provision of another ecosystem good or service. Impacts on geological SSSIs and geoparks.
Environmental 3	**Impacts on groundwater and surface waters**	Release of contaminants (including nutrients), dissolved organic carbon or silt/particulates, affecting suitability of water for potable or other uses, water body status (under WFD) and other legislative water quality objectives, biological function (aquatic ecosystems) and chemical function, mobilisation of dissolved substances. Effects of water abstraction included, such as lowering river levels or water tables or potential acidification. *(Note: Does not include any water abstraction use or disposal issues, as this is covered in 'Environmental 5: Use of natural resources and generation of wastes'.)*
Environmental 4	**Impacts on ecology**	Direct consequences for flora, fauna and food chains, especially protected species, biodiversity and impacts on SSSIs. Introduction of alien species. Significant changes in ecological community structure or function. Impacts of light, noise and vibration on ecology. Use of decontamination equipment that affect fauna (e.g. affecting bird or bat flight, or animal migration, etc). *(Note: Does not include effects on soil and aquatic ecosystems, which are covered in 'Environmental 2: Impacts on soil and ground conditions' and 'Environmental 3: Impacts on water', whilst impacts of light, noise and vibration on humans are covered in 'Social 3: Impacts on neighbourhoods and regions'.)*
Environmental 5	**Use of natural resources and generation of wastes**	Consequences for land and waster resources, use of primary resources and substitution of primary resources within the project or external to it, including raw and recycled aggregates. Use of energy/fuels taking into account their type/origin and the possibility of generating renewable energy by the project. Handling of materials on-site, off-site and waste disposal resources. Water abstraction, use and disposal.
Environmental 6	**Intrusiveness**	Impacts on flooding or increase risk of flooding; alteration of landforms that affect environment, (e.g. a "natural" view). *(Note: Does not include effects on built environment and protection of archaeological resources, which are covered in 'Social 3: Impacts on neighbourhoods or regions', whilst affects on ecology are covered in 'Environmental 4: Impacts on ecology'.)*

Sustainable Remediation Indicators

SuRF SUSTAINABLE REMEDIATION FORUM UK

Social Indicators

ELEMENT	CATEGORY	ISSUES THAT INDICATORS MIGHT NEED TO CONSIDERED
Social 1	**Human health and safety**	Risk management performance of the project in terms of delivery of mitigation of unacceptable human health risks. Risk management performance in the short term, including: risks to site workers, site neighbours and the public from remediation works and their ancillary operations (includes hazardous process emissions such as bioaerosols, allergens, PM10 as well as impacts from operating machinery and traffic movements, excavations, etc).
Social 2	**Ethical and equity considerations**	How are social justice and/or equality addressed? Is the spirit of the 'polluter pays principle' upheld with regard to the distribution of impacts and benefits? Are the effects of works disproportionate to, or more beneficial towards, particular groups? What is the duration of remedial works and are there issues of intergenerational equity (e.g. avoidable transfer of contamination impacts to future generations)? Are the businesses involved operating ethically (e.g. open procurement processes)? Does the treatment approach raise any ethical concerns for stakeholders (e.g. use of genetically modified organisms)?
Social 3	**Impacts on neighbourhoods or regions**	Impacts to local community, including dust, light, noise, odour and vibrations during works and associated with traffic, including both working-day and night-time / weekend operations. Effect of antisocial use of site, and its impact of other regeneration activities. Impacts on the built environment, architectural conservation, conservation of archaeological resources. Effect of the project on local culture and vitality. *(Note: Does not include effects or perceptions of a "natural" view, which is covered in 'Environment 6: Intrusiveness'.)*
Social 4	**Community involvement and satisfaction**	Impacts of works on public access to services (all sectors – commercial, residential, educational, leisure, amenity). Inclusivity and engagement in decision making-process. Transparency and involvement of local community, directly or through representative bodies.
Social 5	**Compliance with policy objectives and strategies**	Compliance of the works with policies, regulatory standards and good practice as set out nationally, by local authority, at the request of community and/or in line with industry working practices and expectations.
Social 6	**Uncertainty and evidence**	How has sustainability assessment been carried out and what has it considered? Quality of investigations, assessments (including sustainability) and plans, and their ability to cope with variation. Accuracy of record taking and storage. Requirements for validation/verification.

Sustainable Remediation Indicators

SuRF SUSTAINABLE REMEDIATION FORUM UK

Economic Indicators

ELEMENT	CATEGORY	ISSUES THAT INDICATORS MIGHT NEED TO CONSIDERED
Economic 1	**Direct economic costs and benefits**	Direct financial costs and benefits of remediation for organisation, consequences of capital and operation costs, and sensitivity to alteration (e.g. uplift in site value to facilitate future development, minimisation of risk or threat of legal action).
Economic 2	**Indirect economic costs and benefits**	Long term or indirect impacts and benefits, such as financing debt, allocation of financial resources internally, changes in site/local land/property values, and fines and punitive damages (e.g. following legal action, so includes solicitor and technical costs during defence). Consequences of an area's economic performance. Tax implications. Financial consequences of impact on corporate reputation.
Economic 3	**Employment and employment capital**	Job creation, employment levels (short and long term), skill levels before and after, opportunities for education and training, innovation and new skills.
Economic 4	**Gearing**	Creating opportunities for inward investment, use of funding schemes, ability to affect other projects in the area / by client (e.g. Cluster) to enhance economic value.
Economic 5	**Life span and project risks**	Duration of the risk management (remediation) benefit, e.g. fixed in time for a containment system); factors tht might impact the chances of success of the remediation works and issues that may affect works, including community, contractual, environmental, procurement and technological risks.
Economic 6	**Project flexibility**	Ability of project to respond to changing circumstances, including discovery of additional contamination, different soil materials, or timescales. Robustness of solution to climate change effects. Robustness of solution to altering economic circumstances. Requirements for ongoing institutional controls. Ability to respond to changing regulation or its implementation.

Appendix 2 – List of criteria

Ecology

1. Impact on ecology (surf)
2. Ecological impact *(Sorvari)*
3. Ecological risks *(Sorvari)*
4. Habitat/Ecology *(Harbottle)*
5. Soil Vapour Intrusion (GoldSet)
6. Short-Term Impacts on Biodiversity and Species Status (GoldSet)
7. Long-Term Impacts on Biodiversity and Species Status (GoldSet)
8. Short-Term Impacts on Habitat and/or Land Use (GoldSet)
9. Long-Term Impacts on Habitat and/or Land Use (GoldSet)
10. Level of risk reduction *(Alvarez-Guerra)*
11. Long-term risks *(Ritchey)*
12. Extension of the affected area *(Bezama)*
13. Pollutants concentration *(Bezama)*
14. Adhesion risks *(Bezama)*
15. Ecological impacts *(Bhargava; Darlington(SER))*
16. Introduction of invasive species *(Bhargava; Darlington(SER))*
17. Changes in ecosystem structure *(Bhargava; Darlington(SER))*
18. Destruction of habitats *(Bhargava; Darlington(SER))*
19. To reduce negative environmental impacts on the site and on the neighborhood including human health risks (harmful substances, noise) *(Pahlen&Glöckner)*
20. Risks to ecosystems (*Bardos 2008)*
21. Ecological habitat *(Yatsalo)*
22. Complete ecological exposure pathways *(Yatsalo)*
23. Habitats and ecology *(Balasubramaniam)*
24. Reduced environmental risks to potential receptors *(Rowe)*
25. Improving ecosystems *(Kearney&Martin)*
26. *Risks* to other targets *(Bardos 2008)*
27. Estimated concentration of contaminant of concern in fish/risk based concentration *(Yatsalo)*
28. Extent of major ecosystem types *(Bhargava; Darlington (SER))*
29. Magnitude of ecological hazard quotient (*Yatsalo)*
30. Impacts on soil *(surf)*
31. Quality/structure of soil *(Harbottle)*
32. Soil Quality (GoldSet)
33. Loss of soil structure and integrity *(Kearney&Martin)*
34. Disturbance to soil *(Bhargava; Darlington (SER))*
35. Soil quality (*Bardos 2008)*
36. Impacts on soil *(Critto)*
37. Improving soil functions *(Kearney&Martin)*
38. Loss of soil function *(Kearney&Martin)*
39. Ground function *(Bardos 2002)*
40. Change in natural resource service *(Becvar (SRT))*
41. Impact on agricultural productivity *(Scholz and Schnabel)*
42. Estimated concentration of contaminant of concern in fish/risk based concentration *(Yatsalo)*
43. Magnitude of ecological hazard quotient (*Yatsalo)*
44. Off-Site Migration (GoldSet)
45. *Water function (Bardos 2002)*
46. Impacts on water *(Critto)*
47. G.W quality *(Harbottle)*
48. G.W quality *(Sorvari)*
49. Groundwater Quality (GoldSet)
50. water quality *(Bowtell)*
51. groundwater quality (*Bardos 2008)*
52. Ground water quality *(Postle)*
53. Ground water quality *(Balasubramaniam)*

54. Free Product (GoldSet)
55. Impacts on water (surf)
56. Risk to water resources *(Bowtell)*
57. Impacts on water *(Critto)*
58. Impacts on water (surf)
59. Risk to water resources *(Bowtell)*
60. Disturbance to surface water bodies *(Bhargava, 2009; Darlington 2009(SER))*
61. Water function (Bardos 2002)
62. S.W quality *(Harbottle)*
63. Surface Water Quality (GoldSet)
64. Free Product (GoldSet)
65. Off-Site Migration (GoldSet)
66. Water quality *(Bowtell)*
67. Emissions to water *(Vik)*
68. Surface water emissions (*Bardos 2008)*
69. Surface water quality *(Postle)*
70. Surface water quality *(Balasubramaniam)*
71. air emissions (*Bardos 2008)*
72. Air *(Postle)*
73. Air quality *(Balasubramaniam)*
74. Impacts on air quality (Rowe)
75. Emissions to air *(Sorvari)*
76. Air quality (pollution) *(Harbottle)*
77. Impacts on air (surf)
78. Emissions to air *(Vik)*
79. Air and atmosphere *(Bardos 2002)*
80. Transportation (of soil material and building debris to off site soil treatment plants, to recycling/disposal or building debris assortment plants)=emissions Units and pumps: long term use =high cumulative energy demand and corresponding emissions (*Schrenk)*
81. Greenhouse Gas Emissions (GoldSet)
82. Carbon dioxide emissions *(Bowtell)*
83. CO2 emissions to the atmosphere *(Becvar (SRT))*
84. GHG emissions (CO2, CH4, N2O) *(Becvar (SRT))*
85. CO2 emissions *(Vik)*
86. GHG due to fossil fuel usage *(van Drunen)*
87. GHG (Rowe)
88. Air quality (global warming) *(Harbottle)*
89. Nitrogen oxides (NOx) *(Becvar (SRT))*
90. Sulfur oxides (SOx) *(Becvar (SRT))*
91. Air emissions from priority pollutants (NOx, SOx, PM) *(Becvar (SRT))*
92. Particulate Matter (PM10) *(Becvar (SRT))*
93. Use of natural resources *(Harbottle)*
94. Regional and global resource management *(Ritchey)*
95. Raw materials consumption *(Alvarez-Guerra)*
96. Consumption of resources *(Bhargava; Darlington (SER))*
97. Resource and energy use (Bardos 2002)
98. Natural resources use (*Bardos 2008)*
99. Resource consumption (e.g. power, water, chemicals) *(Rowe)*
100. Energy consumption *(Sorvari)*
101. Energy consumption (*Alvarez-Guerra)*
102. Energy Consumption (GoldSet)
103. Total energy consumed *(Becvar (SRT))*
104. Energy use *(Vik)*
105. Consumption of energy from non-renewable versus renewable sources *(Bhargava; Darlington(SER))*
106. Transportation (of soil material and building debris to off site soil treatment plants, to recycling/disposal or building debris assortment plants)=substantial consumption of fossil fuels. *(Schrenk)*
107. If the gravel is mined secondary energy consumption is used while mining the gravel. *(Schrenk)*
108. Energy use (*Bardos 2008)*
109. Soil loss *(Sorvari)*

110. Resource recovery when reusing treated contaminated soil or recovering energy during remediation *(Vik)*
111. G.W quantity *(Harbottle)*
112. S.W quantity *(Harbottle)*
113. G.W loss *(Sorvari)*
114. Water required *(Alvarez-Guerra)*
115. Water Usage (GoldSet)
116. Drinking Water Supply (GoldSet)
117. Water consumption *(Bhargava; Darlington (SER))*
118. Ground water quantity *(Postle)*
119. Groundwater quantity lost (*Bardos 2008)*
120. Surface water quantity *(Postle)*
121. Environmental impact when clean gravel is used as filling material=high land consumption. *(Schrenk)*
122. Use of natural resources and generation of wastes *(surf)*
123. Final solid residuals produced *(Alvarez-Guerra)*
124. Residuals production *(Critto)*
125. To minimize waste and maximize recycling and reuse of soil and debris *(Pahlen & Glöckner)*
126. Waste generation by dumping soil on landfill *(Vik)*
127. Generation of wastes requiring off site disposal *(Rowe)*
128. Production of toxic by-products *(Rowe)*
129. Waste *(Harbottle)*
130. Wastes (GoldSet)
131. Waste by-products *(Bello-Dambatta)*
132. Waste creation *(Bardos 2008)*
133. Hazardous Wastes (GoldSet)
134. Waste generation (Sorvari)
135. Reuse referred remediation limits *(Bezama)*
136. Ecologic sustainability *(Costanza)*
137. Environmental impacts (positive and negative) *(Pollard)*
138. Intangible impacts (e.g. on human health and ecosystems) *(Pollard)*
139. Wider environment *(Bello-Dambatta)*
140. Environmental quality *(Yatsalo)*
141. Environmental effectiveness *(Promentilla)*
142. Restoration of environmental resources and potential beneficial uses of land and groundwater *(Rowe)*
143. Compliance with environmental legislation and guidelines *(Rowe)*

Economy

1. Economic impacts (costs) *(Sorvari)*
2. Cost *(Alvarez-Guerra)*
3. Cost *(Bowtell)*
4. Cost *(Yatsalo)*
5. Cost *(Yatsalo)*
6. Any additional management costs incorporated through the desire to minimise risks *(Postle)*
7. Direct economic costs and benefits *(surf)*
8. Sampling or monitoring costs, before remediation. *(Postle)*
9. Prepatory work *(van Drunen*)
10. Design *(Hardisty)*
11. Minimize investment costs *(Ritchey)*
12. Insurances *(Bezama)*
13. Capital costs – initial *(Hardisty)*
14. Initial investment *(Alvarez-Guerra)*
15. Capital costs – future modification *(Hardisty)*
16. Capital cost *(Postle)*
17. Land fill costs *(Bowtell)*
18. Operating and maintenance costs *(Postle)*
19. Sampling or monitoring costs during *(Postle)*
20. Labour costs *(Postle)*
21. Cost of any off-site transport, disposal and treatment requirements *(Postle)*
22. Clean up cost *(Jianbing Li)*
23. Minimize costs for maintenance after remediation *(Ritchey)*

24. Costs (preparation, operation, maintenance, monitoring at all stages of the operation *(Bardos 2008).*
25. Treatment of on-site impacts *(Rowe)*
26. Treatment of off-site impacts *(Rowe)*
27. A combination of the on-site and off-site treatments *(Rowe)*
28. Treatment of hotspots *(Rowe)*
29. Demolition work *(van Drunen)*
30. Supervision *(van Drunen)*
31. Maintenance *(van Drunen)*
32. Replacement cost (van Drunen)
33. Logistics (GoldSet)
34. Engineering *(Hardisty)*
35. Mobilization *(Hardisty)*
36. Decommissioning costs *(Hardisty)*
37. Transportation costs of filling material *(Hardisty)*
38. Preparatory/enabling works *(Hardisty)*
39. Landfill fees *(Hardisty)*
40. Treatment costs *(Hardisty)*
41. Maintenance costs *(Hardisty)*
42. Costs of remediation *(Scholz and Schnabel)*
43. Financial Recoveries Reliability (Maintenance and Repair) (GoldSet)
44. Monitoring costs *(Hardisty)*
45. Monitoring *(Rowe)*
46. Validation costs *(Hardisty)*
47. Post-treatment costs *(Hardisty)*
48. Post-closure measures, control systems *(van Drunen)*
49. Sampling or monitoring costs after remediation. *(Postle)*
50. Duration of remediation *(Harbottle)*
51. Life span and "project risk" *(surf)*
52. Duration of Work (GoldSet)
53. *Overheads*, damage compensation paid to third parties *(van Drunen)*
54. Unplanned delays due to unexpected events render external costs *(Hardisty)*
55. Unplanned events during remediation could render secondary external costs like polluting an aquifer
56. (Hardisty)
57. Potential Litigation (GoldSet)
58. Interception *(Rowe)*
59. Minimize liability *(Ritchey)*
60. Service Reliability and Performance (GoldSet)
61. Technological Uncertainty (GoldSet)
62. Project Flexibility *(surf)*
63. Public Safety (GoldSet)
64. Worker's Safety (GoldSet)
65. Safety/collateral risk (fatality and injury) *(Bhargava; Darlington (SER))*
66. Safety / Accident risk *(Becvar (SRT))*
67. Increased congestion *(Hardisty)*
68. Impacts on health of emissions *(Hardisty)*
69. Noise impacts *(Hardisty)*
70. Increased probability of accidents and fatalities due to transports *(Hardisty)*
71. Environmental costs *(Janikowski)*
72. GHG emissions throughout the whole remediation *(Hardisty)*
73. Land value improvement *(Bowtell)*
74. Land market prices
75. Area´s offer and demand *(Bezama)*
76. Market value of land after remediation
77. Impacts assessed in monetary terms (impacts on local properties) *(Pollard)*
78. Financial impact on local residents *(Balasubramaniam)*
79. Natural capital (ecological services and their systems)*(Hardisty)*
80. Environmental Reserve (GoldSet)
81. Transport models *(Bezama)*
82. Area´s infrastructure *(Bezama)*
83. (Selling, remediation & use) models *(Bezama)*

84. (Public/private partnership) models *(Bezama)*
85. Private or public funding *(Bezama)*
86. National/EU promotions *(Bezama)*
87. Price situation *(Bezama)*
88. Search for investors and users *(Bezama)*
89. Indirect and indirect economic benefits *(surf)*
90. Degree of Opportunities for beneficial uses (of the residual products from remediation) (Alvarez-Guerra)
91. Maximize revenue (Ritchey)
92. Location priority *(Bezama)*
93. Reuse of the Property by the Corporation *(GoldSet)*
94. New public space *(Bowtell)*
95. Economic advantages for the local community
96. Impacts on local business and inward investment (Vik)
97. New jobs *(Bowtell)*
98. New homes *(Bowtell)*
99. Local Job Creation and Diversity (GoldSet)
100. Net Present Value of Options' Costs (GoldSet)
101. Costs of an option *(Pollard)*
102. Impacts on local employment *(Pollard)*
103. Cost benefit analysis *(Bezama)*
104. Cost effectiveness analysis *(Bezama)*
105. Public sector involvement *(Bowtell)*
106. Economic regeneration (Beneficial use for the site and inward investment delivery) *(Bowtell)*
107. Employment creation *(Vik)*
108. Removal of stigma *(Vik)*
109. To ensure cost effectiveness *(Pahlen & Glöckner)*
110. Built capital (income, wealth) Human capital, (health, education) *(Costanza*
111. Social capital (family life, social networks) Economic goal of efficiency *(Costanza)*
112. Cost-effectiveness *(Bello-Dambatta)*
113. Overall cost *(Critto)*
114. *Costs and benefits (Bardos 2002)*
115. Financial affordability *(Promentilla)*
116. Cost-effectiveness *(Janikowski)*
117. Employment/employment capital
118. Gearing *(surf)*
119. Societal benefits (Ritchey)

Socio-cultural

1. Societal considerations *(Bello-Dambatta)*
2. Space use *(Sorvari)*
3. Community impacts *(Bhargava; Darlington (SER))*
4. Third party stakeholder concern *(Postle)*
5. Ethical and equity considerations *(surf)*
6. Social fairness *(Costanza)*
7. Response to Social Sensitivity *(GoldSet)*
8. Image aspects *(Sorvari)*
9. Acceptability *(Harbottle)*
10. Social acceptance *(Alvarez-Guerra)*
11. Acceptance *(Ritchey)*
12. Value formation through public discussion (democracy) *(Costanza)*
13. Social acceptability (Janikowski)
14. Community/public acceptability *(Jianbing Li)*
15. To improve social acceptance through identification of all stakeholders and risk communication *(Pahlen &Glöckner)*
16. Third party stakeholder acceptability *(Postle)*
17. Community acceptability *(Critto)*
18. Social acceptability *(Promentilla)*
19. (more of a project management issue than an issue when comparing between remediation alternatives)

20. Communication and cooperation with public side *(Bezama)*
21. Degree of communication *(Bowtell)*
22. Efficacy of treatment in terms of removal of contaminants *(Rowe; discussed with the public)*
23. Feasibility of remedial technology in terms of operation and licensing *(Rowe; discussed with the public)*
24. Timeframe for remediation to achieve remediation goals *(Rowe; discussed with the public)*
25. Costs *(Rowe; discussed with the public)*
26. Attitude of key parties *(Bowtell)*
27. Mutual trust *(Bowtell)*
28. Levels of experience *(Bowtell*
29. Confidence *(Harbottle)*
30. Time until protection is achieved *(Alvarez-Guerra)*
31. Experience *(Alvarez-Guerra)*
32. Degree in which sediment characterisation are conductive for the alternative *(Alvarez-Guerra)*
33. Degree in which contamination are conductive for the alternative *(Alvarez-Guerra)*
34. Public Safety *(GoldSet)*
35. Worker's Safety *(GoldSet)*
36. Service Reliability and Performance *(GoldSet)*
37. Technological Uncertainty*(GoldSet)*
38. Community involvement and satisfaction *(surf)*
39. Management Practices *(GoldSet)*
40. Risks to public *(Harbottle)*
41. Health risks *(Sorvari)*
42. Level of risk reduction *(Alvarez-Guerra)*
43. Long-term risks *(Ritchey)*
44. Human health *(surf)*
45. Human health exposure *(Bowtell)*
46. To reduce negative environmental impacts on the site and on the neighbourhood including human health risks (harmful substances, noise) *(Pahlen &Glöckner)*
47. Risks (humans)(*Bardos 2008)*
48. Risk reduction: because of the contamination *(van Drunen)*
49. Risks to site users *(Postle)*
50. Risks to the public *(Postle)*
51. Human habitat *(Yatsalo)*
52. Complete human health exposure pathways *(Yatsalo)*
53. Magnitude of maximum cancer risk *(Yatsalo)*
54. Risks to health of the site users *(Balasubramaniam)*
55. Risks to health of the general public *(Balasubramaniam)*
56. Impact of human health *(Scholz and Schnabel)*
57. Reduced health risks to potential receptors Noise *(Rowe)*
58. Legionella issues *(Rowe)*
59. Contaminated matrix removal Hazardous reagents use *(Critto)*
60. Lorry movements *(Kearney&Martin)*
61. Increased noise and traffic *(Vik)*
62. Particulate Matter (PM10) *(Becvar (SRT))*
63. Noise that is disturbing to local inhabitants *(van Drunen)*
64. Noise *(Kearney&Martin)*
65. Impact of human health *(Scholz and Schnabel)*
66. Risks during remediation *(Ritchey)*
67. Risks to site users *(Harbottle)*
68. Human health *(surf)*
69. Risks (humans) *Bardos 2008)*
70. Risk reduction: because of the remedial work.*(van Drunen)*
71. Complete human health exposure pathways *(Yatsalo)*
72. Magnitude of maximum cancer risk *(Yatsalo)*
73. Dust and volatile substances emissions-human health *(Critto)*
74. Dust *(Kearney&Martin)*
75. Release of volatile emissions *(Kearney&Martin)*
76. Odor *(Kearney&Martin)*
77. Cultural Heritage (GoldSet)
78. Impact on the Landscape (GoldSet)

79. Intrusiveness *(surf)*
80. Impact on landscape *(Harbottle)*
81. Quality of Life (During the Project) (GoldSet)
82. Loss of amenity if an area or open space is lost *(Bowtell)*
83. Impacts on neighbourhoods and regions *(surf)*
84. Surrounding land use *(Harbottle)*
85. Land use *(Bowtell)*
86. Surrounding fields use *(Bezama)*
87. Surrounding land use *(Postle)*
88. Site use (*Harbottle)*
89. Short-Term Impacts on Habitat and/or Land Use (GoldSet)
90. Long-Term Impacts on Habitat and/or Land Use (GoldSet)
91. Use for the Public (GoldSet)
92. Potential use *(Bezama)*
93. Situation of the site *(Bezama)*
94. Shift in geographic distribution *(Bhargava; Darlington (SER))*
95. Use of space (*Bardos 2008)*
96. Site use *(Postle)*
97. Reusing contaminated land as opposed to using undisturbed land *(Vik)*
98. Net environmental benefit (Rowe)
99. Situation and legal validity *(Bezama)*
100. Legal risks *(Bezama)*
101. Aggravation factors *(Bardos 2002)*
102. Standards, Laws and Regulations *(GoldSet)*
103. Compliance with policy objectives and strategies *(surf)*
104. Fulfilment of political goals *(Ritchey)*
105. Regulatory permitting acceptability (Jiang bin Li)

Technology criteria

1. Time to complete clean-up Effectiveness in removing a wide range of heavy metal concentrations (Janikowski)
2. Long-term effectiveness (Janikowski)
3. Clean up time (Jianbing Li)
4. Minimum achievable contaminant concentration (i.e. efficiency of remedial alternative) (Jianbing Li)
5. Development status (Jianbing Li)
6. Maintenance requirement (Jianbing Li)
7. Technology availability (Jianbing Li)
8. To ensure technical feasibility (Pahlen&Glöckner)
9. Technical efficiency (Bello-Dambatta)
10. Ratio of impacted area to facility capacity (acres/ million cubic yards) (Yatsalo)
11. Reliability/maintenance (Critto)
12. Technology development status (Critto)
13. Train technology (Critto)
14. Clean-up operations location (Critto)
15. Performance (Critto)
16. Clean-up time (Critto)
17. Implementability (Promentilla)

(Schrenk, 2002, Darlington et al., 2009, Bowtell and Bewley, 2008, Harbottle et al., 2008a, Smith et al., 2010, Alvarez-Guerra et al., 2010, Ritchey, 2008, Bezama et al., 2004, Costanza, 2006, Hardisty et al., 2008, Kearney et al., 1999, Becvar et al., 2009, Vik et al., 2001, Bardos et al., 2002, Janikowski et al., 2000, Jianbing, 2010, Pahlen and Glöckner, 2004, Bardos, 2008, van Drunen et al., 2005, Postle et al., 1999, Bello-Dambatta et al., 2009, Yatsalo et al., 2007, Critto et al., 2006, Balasubramaniam et al., 2007, Promentilla et al., 2006, Scholz and Schnabel, 2006, Rowe, 2004, Pollard et al., 2004, Sorvari and Seppälä, 2010) GoldSET (2010)

Appendix 3 – Laws associated to remediation

Laws connected to remediation Sections of the law that is important to regard when remediating contaminated land according to SEPA (2006).

2nd Chapter 1§ EC	General rules of consideration
2nd Chapter 3§ EC	General rules of consideration, the precautionary principle
2nd Chapter 8§ EC	General rules of consideration, remediation liability
6th Chapter EC	Environmental Impact Assessmenst
9th Chapter 6§ EC	Authorization and notification requirements for hazardous activities
10th Chapter EC	Contaminated sites
10th Chapter 1-8§§ EC	Responsibility for investigations and remediation
10th Chapter 9§ EC	Disclosure Obligations
10th Chapter 10-14§§ EC	Environmental Risk Areas
22nd Chapter 25§ 10p EC	Permit conditions
24th Chapter 5§ EC	Permit review
26th Chapter 9§ EC	Injunctions and prohibitions
26th Chapter 15§ EC	Registration of order or prohibition in the Land Registry
26th Chapter 17-18§§ EC	Correction on the offender's expense
26th Chapter 21-22§§ EC	Disclosure and investigations
28th Chapter 5§ EC	Access to remediate
28th Chapter 6§ EC	Duty of care
28th Chapter 7§ EC	Prohibition on altering equipment
32nd Chapter EC	Damages for some environmental damage and other individual claims
33rd Chapter 1, 3, 4§§ EC	Remediation insurance

Appendix 4 –Decision Support Tools

- Web-hipre: http://www.hipre.hut.fi/
- Expert Choice: http://www.expertchoice.com/
- Decision Lab: http://www.visualdecision.com/dlab.htm
- Criterim Decision plus: http://www.infoharvest.com
- SRT:http://www.afcee.af.mil/resources/technologytransfer/programsandinitiatives/sustainableremediation/srt/index.asp
- Sitewise: http://www.ert2.org/t2gsrportal/SiteWise.aspx
- GOLDset: http://www.gold-set.com/portal/default.html