Technical University of Denmark

Bæredygtighed af afværgemetoder

Notat 1 Litteraturstudium

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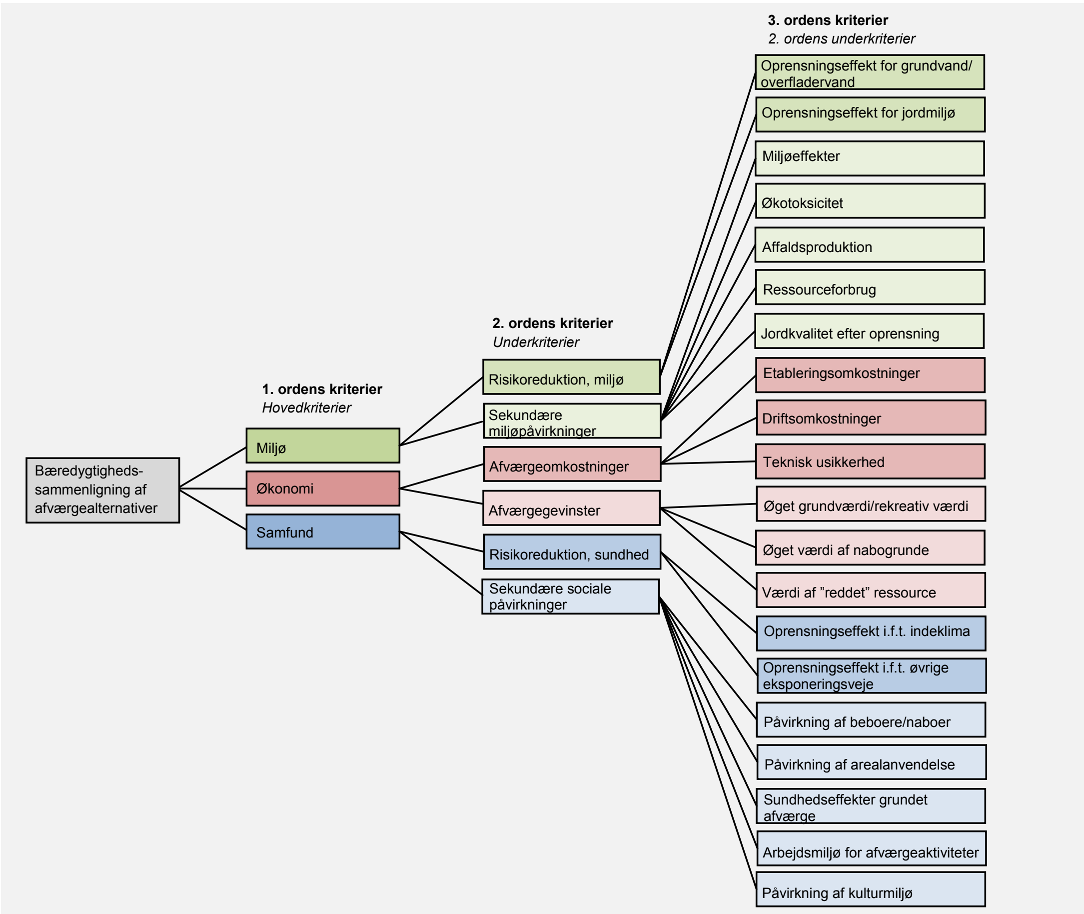
Publication date:
2011

Document Version
Også kaldet Forlagets PDF

Bæredygtighed af afværgemetoder



Notat 1

Litteraturstudium

Gitte Lemming, Philip J. Binning og Poul L. Bjerg

DTU Miljø

December 2011

Forord

Dette notat afrapporterer den indledende fase (fase 1) i projektet *Bæredygtighed af afværgemetoder*, som er et samarbejdsprojekt mellem Region Midtjylland og DTU Miljø, Danmarks Tekniske Universitet. Projektet er knyttet sammen med projektet *NorthPestClean*, som omhandler fastsættelse af oprensningskriterier for pesticidforureningen ved Høfde 42 samt pilotskalatests af oprensning med *in situ* basisk hydrolyse ved Høfde 42.

I projektets første fase er der foretaget et litteraturstudium, der har til formål at kortlægge de eksisterende erfaringer med brug af multikriteriemetoder til beslutningsstøtte for bæredygtig afværge samt udvalgte værktøjer for relaterede områder såsom vandforsyning. Den studerede litteratur omfatter:

- Generel litteratur om multikriterieanalyse og vægtningsmetoder
- Videnskabelige artikler samt faglige rapporter vedrørende anvendelsen af multikriteriemetoder i forbindelse med bæredygtighedsvurderinger af afværge
- Eksisterende værktøjer til bæredygtighedsvurdering af afværge samt relaterede fagområder

Litteraturstudiet vil danne baggrund for den efterfølgende udvikling af et multikriterieværktøj til bæredygtigheds-vurdering af afværgemetoder som finder sted i projektets fase 2.

Som nævnt vil udviklingen af selve værktøjet finde sted i fase 2 og i fase 3 vil værktøjet blive anvendt til at foretage en bæredygtighedsvurdering af 3 oprensningsalternativer for forureningen ved Høfde 42. Det udviklede værktøj vil have generel karakter, således at det kan anvendes til bæredygtighedsvurdering af oprensning af alle typer af forurenede grunde.

En oversigt over projektets tre faser og deres tidsmæssige afgrænsning ses herunder. Litteraturstudiet i dette notat er udført på engelsk således, at det senere kan indgå i en eventuel afrapportering i forbindelse med NorthPestClean projektet.

Projektfaser

Fase 1 (1/9 – 31/12 2011): Litteraturfase og Intro-workshop (Workshop 1)

Fase 2 (1/1 - 31/12 2012): Metodeudviklingsfase og Midtvejs-workshop (Workshop 2)

Fase 3 (1/1 - 1/6 2013): Færdiggørelse af værktøj, case-afprøvning (Høfde 42) og Afsluttende workshop (Workshop 3)

Table of content

Multi-criteria assessment used for sustainability evaluation of site remediation

1 Objectives and coverage of literature study

The objective of the conducted literature study is to provide an overview of the previous experiences with the use of multi-criteria assessment (MCA) methods for sustainability evaluation for site remediation. The literature study will be used as a starting point for the tool development in this project.

In our literature survey we focused on the remediation field, but included a few selected studies from the related fields of harbor or river sediment remediation and water supply. Furthermore, in the initial state the general literature on multi-criteria assessment methods and weighting methods was studied. Thus, as presented in Table 1, the studied literature covers:

- General literature on multi-criteria assessment methods and weighting methods
- Scientific papers regarding the use of multi-criteria assessment methods for sustainability appraisal of remediation and related fields
- Existing tools and frameworks for sustainability assessment of remediation and related fields

Table 1. Overview of literature included in literature study

Issue	Reference	Type
Multi criteria analysis (MCA) and weighting methods	*Linkov et al. (2004). Multi-criteria decision analysis: a framework for structuring remedial decisions at contaminated sites*	Book chapter
	Coyle (2004). The analytical hierarchy process. Introduction.	Web material
	Department for Communities and Local Government (2009): Multi-criteria analysis: a manual	Report
	Linkov and Seager (2011).Coupling Multi-Criteria Decision Analysis, Life-Cycle Assessment, and Risk Assessment for Emerging Threats	Journal paper
Scientific papers on MCA used for sustainability evaluation of remediation or related field	*Rogers et al. Yatsalo et al. (2004). Combining expert judgment and stakeholder values with PROMETHEE: A case study in contaminated sediments management*	Book chapter
	Balasubramaniam et al.(2007). Improving petroleum contaminated land remediation decision-making through the MCA weighting process	Journal paper
	Harbottle et al. (2006). Assessing the true technical/environmental impacts of contaminated land remediation	Conference paper Journal paper
	Harbottle et al. (2008). Sustainability of land remediation. Part 1: overall analysis	Journal paper
	Kim et al. (2010). Multicriteria Decision Analysis To Assess Options for Managing Contaminated Sediments	Journal paper
	Schädler et al. (2011). Designing sustainable and economically attractive brownfield revitalization options using an integrated assessment model	Journal paper
	Sparrevik et al. (2011), Use of multicriteria involvement processes to enhance transparency and stakeholder participation at Bergen harbour, Norway	
Existing tools for sustainability evaluation of remediation or related field	*GoldSET, Golder Associates*	Commercial software
	Godskesen et al. (2011). Assessing the most Sustainable Alternative for Production of Drinking Water – ASTA a decision support system	Excel-based tool
Networks on sustainable remediation and other sources	*Lundie et al. (2008). Sustainability framework. Part A: Methodology for evaluating the overall sustainability of urban water systems*	Report
	Rosen et al. (2009). Multikritirieanalys for hållbar sanering	Report
	SuRF-UK (2010). A Framework for Assessing the Sustainability of Soil and Groundwater Remediation	Report
	NICOLE (2010) Sustainable remediation roadmap	Report
	SURF US whitepaper, framework paper and Metrics Toolbox (2011)	Papers + reports

The reason for including selected studies from other fields than remediation was that the literature search located only 5 studies that exemplified the use of MCA for sustainability appraisal of contaminated site remediation. These were published during the recent 5-year period. The issue of sustainable remediation has, however, gained increased focus in the US as well as in Europe in recent years and this has resulted in the creation of a number of networks dealing specifically with the issue of sustainable remediation. These networks seek to bring together environmental agencies, industries and consultancies in defining a framework for bringing sustainability evaluations into all phases of remedial projects from site investigation to remedial design and operation. Sustainable Remediation Forum in the US (SURF) issued a sustainable remediation whitepaper in 2009 (SURF, 2009) followed by number of guidance papers (e.g. Holland et al., 2011) and Sustainable Remediation Forum in the UK, (SuRF-UK) has published a framework for sustainable remediation (SuRF-UK, 2010) as well as a set of recommended sustainability indicators (SuRF-UK, 2009; SuRF-UK, 2011). In addition, the Swedish program of sustainable remediation, *Hällbar Sanering,* (Rosén et al., 2009) has published a methodology for sustainability appraisal using MCA and the Network of Industrially contaminated land in Europe (NICOLE, 2010) has published a so-called *roadmap for sustainable remediation*.

2 Definition of sustainable remediation

The Brundtland Report by the World Commission on Environment and Development (UN, 1987) defined sustainable development as

"*development that meets the needs of the present without compromising the ability of future generations to meet their own needs*".

As an outcome of the 1992 UN Conference on Environment and Development, the Agenda 21 action plan recommended that all countries develop national strategies for sustainable development and emphasized the importance of broad public participation in decision making as an integral part of sustainable development (UN, 1992).

In the 2002 World Summit on Sustainable Development, the definition was further expanded to encompass the three pillars of sustainable development as outlined in the Johannesburg Declaration (UN, 2002):

"Accordingly, we assume a collective responsibility to advance and strengthen the interdependent and mutually reinforcing pillars of sustainable development - economic development, social development and environmental protection - at the local, national, regional and global levels"

This 3-pillar concept of sustainability has been widely adopted although not universally accepted, e.g. some critics claim that the concept is incomplete and that e.g. culture should be a fourth pillar to be included in sustainable development (Nurse, 2006). Furthermore, the 3-pillar concept has also been depicted in different ways illustrating the different interpretations (see Figure 1): as 3 independent pillars leading to sustainable development, as interlocking circles illustrating the interdependence between the 3 dimensions and as concentric circles emphasizing that the biosphere is the foundation for the society, which again is a foundation for the economy.

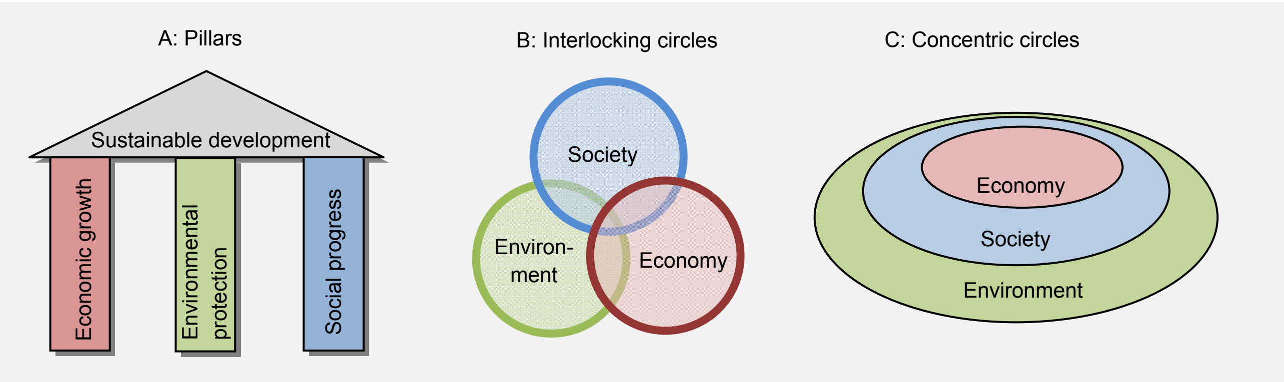


Figure 1.Three representations of sustainable development. Modified after IUCN (2006)

The definitions of sustainable remediation encountered in the studied literature have generally incorporated the 3-pillar concept of sustainability. As an example, the Sustainable Remediation white paper from US SURF (2009) includes the following definition:

"*Sustainable remediation can be defined as a remedy or combination of remedies whose net benefit on human health and the environment is maximized through the judicious use of limited resources [...] The term sustainable remediation considers the impacts and influences of sustainability's triple bottom line (i.e., environmental, societal, and economic) while protecting human health and the environment. As such, sustainable remediation supplements the protection of human health and the environment with the consideration of broader benefits and impacts, as measured by metrics*"

The definition of sustainable remediation in the 2010 SuRF-UK framework (2010) is similar:

"*The practice of demonstrating, in terms of environmental, economic and social indicators, that the benefit of undertaking remediation is greater than its impacts and that the optimum remediation solution is selected through the use of a balanced decision-making process*"

In a paper by Bleicher and Gross (2010) an anthropocentric view of sustainable remediation is presented. Here the main goal is to ensure the human existence development potential, whereas the ecosphere only holds value in the sense that it is a prerequisite for maintaining the society's production potential. According to this concept, sustainable development should first ensure the human existence, then the society's production potential and finally the society´s possibilities for development and action.

2.1 Sustainability indicators for sustainable remediation

Based on a review of published sustainability indicator sets, SuRF-UK (2009) developed a set of environmental, economic and social indicators, see Table 1. There are 6 headline indicators in each of the 3 dimensions of sustainability. These indicators were updated and described in a report from 2011 (SuRF-UK, 2011). The sustainability framework by SuRF-UK (2010) does not outline a complete methodology and set of tools to be used for a sustainability evaluation. It defines the framework and leave open to develop sub indicators for each of the headings in Table 2 and to select appropriate tools for evaluating and weighting each indicator.

Table 2. Headline indicator categories defined by SuRF-UK (2011)

Environmental	**Economic**	**Social**
- Impacts on air - Impacts on soil and ground conditions - Impacts on water - Impacts on ecology - Use of natural resources and generation of wastes - Intrusiveness	- Direct costs and direct economic benefits - Indirect costs and indirect economic benefits - Employment and employment capital - Induced economic gearing - Life span and project risks - Project flexibility	- Human health and safety - Ethical end equity considerations - Impacts on neighbourhoods or regions - Community involvement and satisfaction - Compliance with policy objectives and strategies - Uncertainty and evidence

3 Environmental assessment of remediation

Environmental assessment methods such as life cycle assessment (LCA) has gained increased focus during the recent 10-year period in order to quantify the wider environmental impacts of contaminated site remediation. Furthermore, a number of simplified assessment tools have been developed with the aim of quantifying specifically the environmental impacts related to remediation projects. Examples of such tools are Sitewise™ (NAVFAC et al., 2011), Sustainable Remediation Tool (SRT) (AFCEE, 2010) and Remediation Strategy for Soil and Groundwater Pollution (RemS) (Weber et al., 2011). In addition US EPA (2008) issued their Green Remediation Primer in 2008 focusing on incorporating better environmental practices in relation to management and remediation of contaminated sites.

3.1 Life cycle assessment (LCA)

Life cycle assessment (LCA) is a systematic and widely used decision support tool for environmental assessment in all fields. It is a quantitative method aimed at comparing the environmental impacts related to fulfilling a defined function. LCA seeks to assess the environmental consequences of human activities such as remediation by aggregating environmental flows related to all parts of the life cycle of the remediation activity from “cradle to grave” and translating them to environmental impacts such as global warming, acidification etc.

A review on the literature on LCA and remediation is given in Lemming et al. (2010a). In addition to the studies included in the literature review, newer LCA studies are represented by Sanscartier et al. (2010), Lemming et al. (2010b) and Sparrevik et al. (2011b). In LCA the various environmental impacts are quantified in different units. By dividing with a reference flow such as e.g. the impacts of an average person, all impacts can be expressed in a common unit for instance person equivalents (PE). Different life cycle impact assessment methods exist and for some of the impacts, especially the toxic impacts, the quantification methods vary between the methods, whereas a larger consensus exist for impacts such as global warming, acidification, eutrophication and photochemical ozone formation.

3.2 Simplified environmental assessment tools aimed at the remediation field

As mentioned above, environmental assessment tools have been developed specifically for the application to the remediation field. In the US, two tools have been developed, these are the SiteWise™ tool developed by the US Navy, US Army Corps of Engineers, and Battelle (Version 2, NAVFAC et al., 2011) and the Sustainable Remediation Tool (SRT) developed by the Air Force Center for Engineering and the Environment (AFCEE, 2010). SiteWise is currently the most advanced of the two tools and includes the entire life cycle of a large part of the consumables in the remediation projects.

In Denmark, the tool Remediation Strategy for Soil and Groundwater Pollution, RemS, (Weber et al., 2011) has been developed with the specific aim to provide a life-cycle based assessment of the environmental impacts related to remediation projects. As opposed to SiteWise and the SRT tool, RemS does not stall at the inventory of emissions but translates and groups them into a number of potential environmental impacts. Furthermore, all consumables are included in the life cycle assessment, which is therefore more complete than for the two other tools. Another important issue is that the data in the tools are specific to the place they were developed. Thus, the American tools include e.g. electricity mixes for each American state, whereas the Danish tool includes electricity mixes for average Danish, Norwegian, Swedish and European conditions.

The quantitative metrics/indicators included in the three tools can be seen in Table 3. It is clear that the three tools focus mostly on the environmental aspects of sustainability; however few other indicators are included such as remediation cost (SRT and RemS) and accident risk (SiteWise and SRT). However, none of them can be described as sustainability evaluation tools.

3.3 Green Remediation initiative by US EPA

In 2008 US EPA published a “Green Remediation Primer” (US EPA, 2008), which is aimed at incorporation of sustainable environmental practices into the remediation of contaminated sites in order to minimize the environmental impacts associated with remediation. The suggestions for best management practices for all parts of the remediation project aim to:

- Conserve water
- Improve water quality
- Increase energy efficiency
- Manage and minimize toxics
- Manage and minimize waste, and
- Reduce emissions of criteria air pollutants and greenhouse gasses

In addition to the Green Remediation Primer, a methodology for environmental footprint assessment is under development by US EPA (US EPA, 2011). The metrics in the methodology are similar to those of the SiteWise tool, but the methodology also focuses on waste production and recycled content of consumables.

Table 3. Overview of metrics/indicators included in the three tools Sitewise, Sustainable Remediation Tool (SRT) and Remediation Strategy for Soil and Groundwater Pollution (RemS). Only quantitative indicators of the tools are included.

Tool	SiteWise™ (NAVFAC et al., 2011)	Sustainable Remediation Tool (SRT) (AFCEE, 2011)	Remediation Strategy for Soil and Groundwater Pollution (RemS) (Weber et al. 2011)
Environmental metrics/indicators included	- Greenhouse gasses (t) - Nitrogen oxide emissions (t) - Sulfur oxide emissions (t) - Particulate matter (t) - Energy usage (MJ) - Water usage (m^3) - Resource consumption (t)	- Carbon dioxide emissions (t) - Nitrogen dioxide emissions (t) - Sulfur oxide emissions (t) - Particulate matter (t) - Total energy consumed (MJ)	- Global warming (kg CO_2-eq) - Acidification (kg SO_2-eq) - Eutrophication (kg NO_3-eq) - Photochemical ozone formation (kg C_2H_4-eq) - Human toxicity (m^3 air, water, soil) - Ecotoxicity (m^3 water, soil) - Waste generation (kg) - Resource consumption (kg) - Total energy consumed (MJ)
Other metrics/indicators	- Accident risk	- Technology cost (USD) - Safety/accident risk (lost hours, injury risk)	- Remediation cost (DKK)

4 Multi-criteria analysis (MCA)

A sustainability assessment for remediation of a contaminated site cover evaluation of environmental, economic and social aspects and will comprise evaluations of a wide range of indicators, which are expressed in many different units or as qualitative statements. The assessment integrates information from a variety of sources including risk assessment, environmental assessment, cost- or cost-benefit analysis as well as stakeholder preferences. Multi-criteria analysis (MCA) can be applied to integrate all these aspects in an overall analysis that identifies the best alternative or ranks all compared remedial alternatives based on their performance on the included criteria.

Different types of multi-criteria analyses exist of which some of the most applied methods are value presented below, these are value function methods, outranking methods and compensatory methods. This is followed by an introduction to methods for deriving criteria weights and values used in the value function method.

4.1 Value function methods/ Multi-attribute value methods

Value function methods (also referred to as multi attribute value methods) are based on the decision theory developed by Keeney and Raiffa (1976). In this type of analysis the preferences of the decision maker is represented by a mathematical function (*F*) describing the value (v_i) associated different performances (x_i) on each criteria (i) from 1 to n for an alternative *x*:

Equation 1: $$v(x) = F(v_1(x_1), \ldots, v_n(x_n))$$

The value function thus transforms the performance on the different criteria (costs, risks etc.) to a common dimensionless scale. The decision maker is assumed to be rational, i.e. chooses the alternative which maximizes the value function. The method is *compensatory*, meaning that criteria with high scores can compensate for other criteria with low scores.

Utility function methods (also referred to as multi attribute utility methods) are similar, but extend the analysis to cover probability distributions and uncertainty.

Linear additive model
The most widely used form of the value function method (Equation 1 is a linear additive model, where the overall value, *v*, of an alternative *x,* is calculated based on the sum of each individual criteria value, $v_i(x_i)$, and the associated weight, w_i:

Equation 2: $$v(x) = \sum_{i=1}^{n} w_i v_i\,(x_i)$$

n is the number of total criteria, *i*, The weights reflect the relative importance of the criteria and sum to one. An important prerequisite for using the linear additive model is that all criteria are independent.

4.2 Outranking methods
In outranking a pairwise comparison is made between the performances on all criteria for the different alternatives. Alternative A outranges alternative B if it performance better on some criteria and at least equally well on the remaining criteria. Hereby the dominating alternative, which is better than or at least as good as the remaining alternatives for all criteria is identified. Different algorithms exist to identify the best alternative and/or to rank the analyzed alternatives. Outranking methods of the types PROMETHEE and ELECTRE are the most often applied methods. Outranking methods are especially useful, when criteria performances cannot easily be aggregated to a total score (Linkov et al., 2004).

4.3 Non-compensatory methods
In non-compensatory methods minimum requirements (threshold values) for the performance of the criteria are defined beforehand. These requirements are absolute and must be fulfilled in order for an alternative to be assigned as the best. Thus in non-compensatory methods a bad performance on one criterion cannot be compensated for by good performances on other criteria. As an alternative to the non-compensatory model, an optimization model can be applied, where the alternative that is closest to fulfilling the criteria is found (Linkov et al., 2004). The non-compensatory model can also be combined with the linear additive model as done by Rosén et al. (2009), where negative scores indicate that the performance is negative compared to the initial situation and the alternative therefore cannot be described as a strong sustainability.

4.4 Derivation of criteria weights
Different methods exist for derivations of criteria weights to be used in the value function methods. Some of the methods described below (e.g. AHP and SMART) can be used for the whole process of assigning value and weighting. Here we only look at their use for elicitation of criteria weights.

Direct weighting
Direct weighting is here used to describe the procedure, where weights are given directly to each criterion. This can either be done by distributing e.g. 100 points between the criteria and then calculate the normalized weights (i.e. weights that sum to one) or they can be given as normalized weights directly.

Analytical hierarchy process (AHP)
The analytical hierarchy process (AHP) (Saaty, 1987) is based on the linear additive model, but uses a pairwise comparison routine to develop criteria weights. This procedure is based on the presumption, that it is easier to make relative than absolute comparisons. In AHP the weights are developed by comparing the importance of two criteria at a time on a scale from 1 to 9, where 1 states an equal preference, whereas 9 states a very strong preference for one of the criteria. The preferences between criteria are listed in a matrix and the weight for each single criterion is determined by the principal eigenvector of the matrix or it can be approximated as done in the example in Box 1 below.

Due to its transparency and simplicity, AHP is a commonly applied methodology for development of weights in multi-criteria analyses (Yatsalo et al., 2007). One of the important critical issues is, however, the so-called “rank reversal” problem, which means that the original ranking of a set of criteria may change if a new criterion is introduced (Yatsalo et al., 2007). Additionally, it has been criticized that the coupling between the verbal description of the preferences and the associated scores is not theoretically founded (Department for Communities and Local Government, 2009). The method also accepts a certain level of inconsistency in the stated preferences in case of 2 or more criteria. Therefore, the level of inconsistency should be investigated through the calculation of a Consistency Ratio (CR), which describes the degree of inconsistency compared to a random statement of preferences. If CR is below 0.1 the level of inconsistency is satisfactory. Refer to e.g. Coyle (2004) for calculation of CR.

Box 1. Exemplification of the use of AHP for weight derivation

Analytical hierarchy process (AHP)

For a linear additive model (Equation 2) with the 3 criteria C1, C2 and C3, we wish to develop weights using AHP. The criteria are listed in a matrix and a pairwise comparison of the importance is done using the following scale:

How important is C1 compared to C2?

1: Equal preference/equal importance
3: Moderate preference/Moderately more important
5: Strong preference/Strongly more important
7: Very strong preference/Very strongly more important
9: Extremely strong preference/Extremely more important

2, 4, 6 and 8 denote compromises between the above mentioned intensities

Weight derivation

The matrix is completed by comparing two criteria at a time. Note that the diagonal always will be composed by 1 and that the numbers below the diagonal (marked in grey) follow directly as the reciprocal values of the numbers above the diagonal. The geometric mean (the n^th^ root of the product) is calculated for each row. The weight, w_i, for each criteria is found by dividing the geometric mean by the sum of the 3 geometric means:

	C1	C2	C3
C1	1	5	9
C2	1/5	1	3
C3	1/9	1/3	1

Geometric mean:		w_i:
$(1\cdot5\cdot9)^{1/3}$	= 3.5568	0.751
$(1/5\cdot1\cdot3)^{1/3}$	= 0.8435	0.178
$(1/9\cdot1/3\cdot1)^{1/3}$	= 0.3333	0.070
Sum	4.7335	1.0

Some studies have used AHP with an altered scale, e.g. Pöyhönen and Hämäläinen (2001), who found that using a ”balanced score” (1, 1.22, 1.5, 1.86, 2.33, 3, 4, 5.67, 9) gave a higher consistency with other weighting methods. In a decision support system for contaminated sediment remediation, Sparrevik et al. (2011a) replaced the original 9-step scale with a less comprehensive 3-step scale comprising neutral preference (1), strong preference (5) and extremely strong preference (9).

Simple Multi-Attribute Rating Technique (SMART and SMARTER)

The SMART method (Edwards, 1977) is composed of two steps. Initially all the criteria are ranked based on their importance. In step two 10 points are assigned to the least important criteria. The relative importances of the remaining criteria are then expressed by assigning points of above 10. Finally the normalized weights are calculated, i.e. weights that sum to 1. A shortcoming of this method is that the importance of the criteria are not related to the value ranges of the criteria (Edwards and Barron, 1994).

SMARTER (Edwards and Barron, 1994) is a new version of SMART, which is based on the rank order centroid method, i.e. only the criteria ranking order is used to derive the weights. In SMARTER the weight of a criterion ranked i^{th} among n criteria the weight becomes:

Equation 3: $$w_i = \frac{1}{n}\sum_{k=i}^{n}\frac{1}{k}$$

Swing weighting

In swing weighting (von Winterfeldt and Edwards, 1986) the criteria ranges are built into the decision process. The decision maker is faced with a situation where all criteria are at their worst level. He is then asked to change one criterion to its best level and assign 100 points to this criterion. Next he changes the second most important criteria to its best level and assigns a value below 100 to the criteria. The procedure is continued until all criteria have been considered. Finally the points are used to calculate normalized criteria weights.

4.5 Methods for transforming indicator results to a common scale

In value function methods such as the linear additive model, the indicator results expressing the performance on each of the criteria must be transformed into a common value scale. Different approaches for assigning such values are presented below.

The min-max approach

In the min-max approach, the best criteria result receives the maximum score i.e. 100 points, while the worst score receives the lowest score, i.e. zero points. A score is given to all criteria results in between by a linear interpolation between the best and worst result (Lundie et al., 2008). A problem with the min-max method is that it doesn't take the possible ranges and uncertainty of the criteria result into account. It may for instance be that two indicator results are not significantly different, but by applying this method they will receive very different scores (Rosén et al., 2009).

The ranges approach

In the ranges approach maximum and minimum boundaries are defined for each criterion and used as the basis for assigning scores. It is therefore not certain that the score in a given evaluation will distribute from zero to 100, instead it is more likely that the minimum score is higher than zero and the maximum score is lower than 100 (Lundie et al., 2008).

Qualitative indicator results

For some indicators the performance may be given as qualitative statements such as "high", "medium" or "low" impact or rated based on classes. In this case, the quantitative statements can be translated into a quantitative scale in the same way as done with quantitative results. Thus the min-max or ranges approach can be applied. Again it should be noted that the min-max approach may exaggerate the difference between the options as is the case for quantitative results (Lundie et al., 2008).

5 MCA used for sustainability evaluation for site remediation and related areas

The literature study located 5 studies that used a multi-criteria assessment method for a sustainability evaluation of contaminated site remediation. Due to the limited number, the study was expanded to cover selected studies within the related fields of sediment remediation (3 studies) and water supply (2 studies). Table 4 gives an overview of the aim and methodology of each study as well as a listing of the included first and second level criteria used in the 10 studies covered in this review.

The low number of relevant studies located for contaminated site remediation indicates that the use of multi-criteria methods for sustainability evaluation is still limited. Although there has been an increased focus on sustainable remediation in recent years, e.g., exemplified by the establishment of Sustainable Remediation Forums in the US and UK, these have initially been focused on defining the framework for sustainable remediation, whereas they have not specified or developed tools to be used for the sustainability assessment.

Of the five MCA studies related to contaminated site remediation only 4 (Finn et al., 2011; Harbottle et al., 2008; Rosén et al., 2009; Schädler et al., 2011) explicitly state that the aim of the MCA is to perform a sustainability evaluation, whereas the objective of Balasubramaniam et al. (2007) is to improve the decision process of petroleum contaminated sites by involving the stakeholders in the elicitation of weights. Of the 4 studies dedicated to sustainability assessment it should be noted that the commercial GoldSET tool was included although a complete methodology description is not publicly available. This review is therefore based on a conference presentation by Finn et al. (2011). Furthermore It is also worth noting, that the study by Schädler et al. (2011) concerns the sustainability of different land use applications for brownfield sites and therefore have a slightly different focus than the other papers that compare different remediation methods for a contaminated site.

All of the reviewed studies, except Balasubramaniam et al. (2007), Rogers et al. (2004) and Kim et al. (2010) use a hierarchical criteria structure (exemplified in Figure 2) with at least two levels. In the following, we will use the term *first level criteria* to describe the overarching sustainability dimensions (e.g. environment, economy and society), *second level criteria* describe the subcriteria associated with each of the first level criteria, *third level criteria* describe the subcriteria of the second level criteria and so forth.

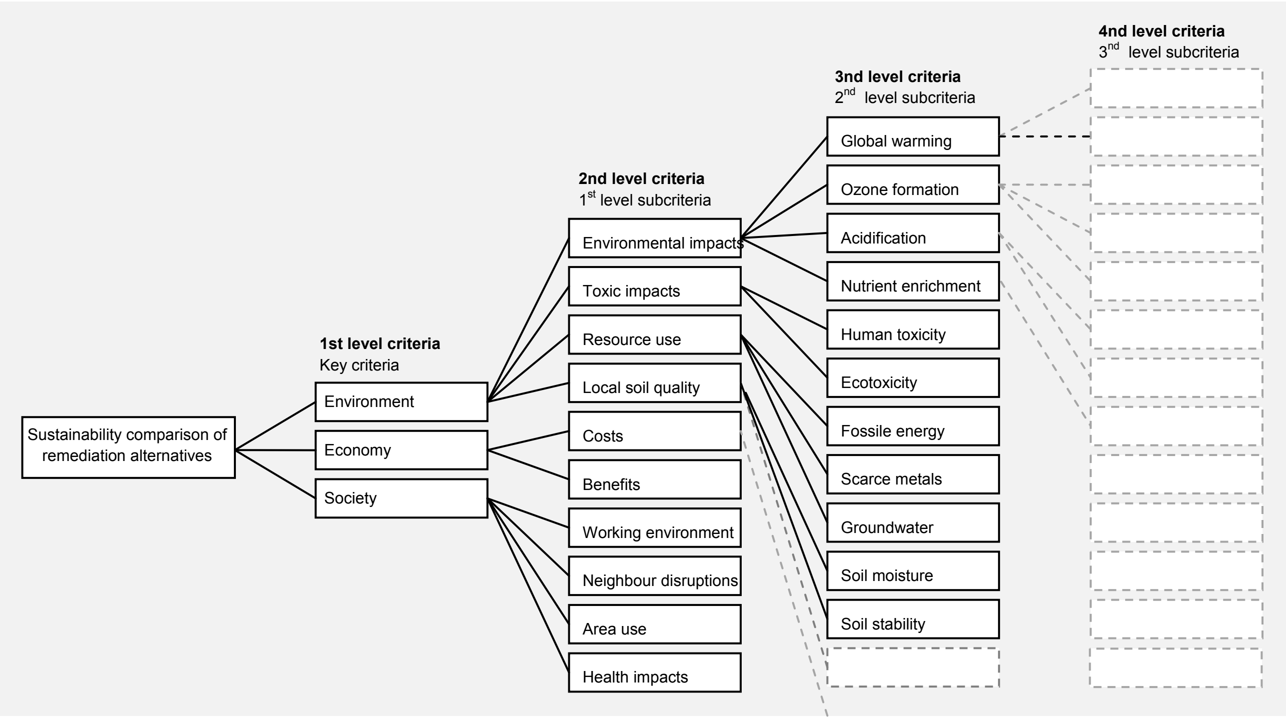


Figure 2. Example of a hierarchical criteria structure

5.1 First level criteria

Based on the selection of first level criteria used in the reviewed studies it is concluded that a large part of the studies (4 out the 9) based their sustainability assessment on the 3 previously defined dimensions of sustainable development: the environmental, social and economic dimension. One of these (Sparrevik et al., 2011a) expanded the environmental criterion to include also human health. Three studies used these 3 dimensions of sustainability but added additional first level criteria being technical aspects (Kim et al., 2010; Lundie et al., 2008), human health (Harbottle et al., 2008; Lundie et al., 2008) and site use (Harbottle et al., 2008). Balasubramaniam et al. (2007), Rogers et al. (2004) and Kim et al. (2010) included only one level of criteria, which were not grouped under the headings of environmental, social and economic impacts, although some of them were similar to the second order criteria used in the above mentioned studies. Schädler et al. (2011) used 3 levels of criteria of which the first level is listed in Table 2. The applied criteria differ substantially from the other studies, which may be explained by the different scope of this study as mentioned above.

5.2 Second level criteria

All studies include environmental criteria in their MCA, however the number of second level environmental criteria ranges from 2 (Sparrevik et al., 2011a; Kim et al., 2010) to 14 (GoldSET tool, in Finn et al., 2011), with an average of 6. According to Lundie et al. (2008) seven criteria are the maximum number of criteria that a stakeholder can relate to at a time and recommends to minimize the number, e.g. by removing those that are not important for the specific site or criteria that scores similarly for all alternatives. Godskesen et al. (2011) reduced the number of second level environmental criteria by grouping them into fewer categories (total environmental impacts, toxic impacts, resource impact) which represents aggregated scores of a number of subcategories in targeted person equivalents (PET) or person resources (PR) based on a life cycle assessment (LCA). As the only study, Harbottle et al. (2008) differentiates between local and global environmental impacts.

On average the studies include 4 social and/or human health second level criteria, which is significantly fewer than for the environmental dimension. As mentioned previously some studies included human health as an individual dimension which causes human health to be weighted higher in the assessment than if being grouped with social indicators. Rosén et al. (2009) and the GoldSET tool (in Finn et al., 2011) includes impacts to the cultural environment within the social dimension.

The economic dimension was handled in different ways in the studies. Three studies expressed it by the financial costs (Lundie et al., 2008; Kim et al., 2010; Rogers et al., 2004), three studies focused on the impact on the local economy in the affected communities (Balasubramaniam et al., 2007; Schädler et al., 2011; Sparrevik et al., 2011a) and three studies used a cost-benefit analysis (Finn et al., 2011; Godskesen et al., 2011; Rosén et al., 2009). Harbottle et al. (2008) excluded the economic dimension, but in an earlier study (Harbottle et al., 2006) the financial costs and change in estimated land value was used.

5.3 MCA methodology, weighting and scoring methods

The linear additive model (Equation 2) was applied in all studies except Rogers et al. (2004), who applied the outranking method PROMETHEE. In addition to the linear additive model, Balasubramaniam et al. (2007) also applied the outranking method ELECTRE III. Rosén et al. (2009) combined the linear additive model with a non-compensatory approach where criteria obtained a negative score if the impact was negative compared to the initial situation. The negative scores could not be compensated for by positive scores and the term *weak sustainability* was used to describe the situation where the most sustainable alternative obtained a negative scores in at least one of the 3 first level criteria of ecological, social and economic aspects as opposed to *strong sustainability* where none of the first level criteria were negative.

The applied method for weighting the first level and/or second level criteria vary across the studies from equal weighting (Rosén et al., 2009), to direct weighting (Schädler et al., 2011), swing weighting (Balasubramaniam et al., 2007; Kim et al., 2010), the Rank Centroid method (Godskesen et al., 2011), analytical hierarchy process (Sparrevik et al. 2011, Godskesen et al. 2011, Roger et al. 2004) and different types of relative weightings (Finn et al., 2011; Harbottle et al., 2008). For all studies using weights, the derived weights are site-specific.

The min-max approach was the most often used method for assigning values to indicator scores in the studies. Godskesen et al (2011) used a s*hare approach* where scores ranging from zero to one were assigned on the basis of the share of all alternatives' indicator scores on the specific criteria.

5.4 Summary of general recommendations from the reviewed studies

The reviewed studies stressed that the advantages of using MCA for sustainability assessment of contaminated site remediation and similar environmental decision making are that it adds structure and robustness to the decision process and provides a good documentation of criteria (Sparrevik et al., 2011a), and that it gives a systematic and transparent process (Rosén et al., 2009; Kim et al., 2010). The possibility for involvement of stakeholders to participate in the decision process was also stressed as an important advantage. Balasubramaniam et al. (2007) recommended that ideally participants should comprise experts, stakeholders and the public and that the number of participants should increase with increasing scale of the decision problem.

Kim et al. (2010) noted that it should be kept in mind that MCA should not be used with the expectation that it will single out the "correct" or even "optimal" solution, as probably no option will be "optimal" for all decision criteria. Instead the strength of MCA is to visualize the trade-offs among multiple conflicting criteria. As a deficit of the MCA method, it usually doesn't incorporate uncertainty in the performance scores. Therefore sensitivity analyses are very important to include in the sustainability assessment (Rosén et al., 2009). Balasubramaniam et al. (2007) used both the linear additive model and an outranking method in their study and found that these did not show the exact same ranking of the assessed remediation scenarios. They therefore recommended that more than one MCA technique is used in order to test the robustness of the result.

5.5 Findings based on the literature study

The literature study has shown that the use of MCA for sustainability comparison of remediation options for a contaminated site is very limited. It also showed that although a number of frameworks for sustainable remediation have been issued during recent years, there has been less focus on the tools and methods to be used for the assessment of sustainability indicators. The reviewed MCA studies for sustainability assessment of remediation alternatives and related fields revealed that most studies include the three overarching dimensions (first level criteria) of environmental, societal and economic impacts and use these as headings for a number of subcriteria. In addition to these three first level criteria many studies found it necessary to include addition first level criteria such as human health or technical aspects.

The literature study also revealed that the linear additive form of the value function method is the most often applied MCA methodology within this field. With the diverse types of criteria included and the fact that some of these may be evaluated in qualitative ways, the linear additive model is more applicable than the general form of the value function. Outranking methods is another good choice for this type of MCA and this was the second most applied method in the reviewed studies.

A number of different weighting methods for determining criteria weights were applied in the studies using the linear additive model. The AHP was found to be user friendly, however it may be problematic to ensure a common understanding of the 9-step scale (Sparrevik et al., 2011a). Balasubramaniam et al. (2007) recommended the use of the swing weighting method and mentions that measures to reduce inconsistency may be taken by asking participants the same questions twice and to spent more time on explanation of the method. A way to ensure a more robust weighting set may also be to apply more than one weighting method.

Table 4. Overview of aim, methodology and applied 1st and 2nd level criteria of multi-criteria sustainability studies in the literature. Note that only the 1st level criteria are listed for the study by Schädler et al. (2010) and that only 1st level criteria are used in the studies by Balasubramaniam et al. (2007), Rogers et al. (2004) and Kim et al. (2010). The headings "Environmental"," Social", "Economic" etc. are therefore not a part of the original criteria hierarchy of these 3 studies.

			1st level criteria					
Reference	**Aim**	**Methodology**	**Environmental/ecological**	**Social/societal**	**Economic**	**Human health**	**Other**	
Remediation of contaminated soil/groundwater								
Harbottle et al. (2006; 2008)	Sustainability assessment focusing on technical/ environmental sustainability	Linear additive method *Scoring:* The alternative with the highest/lowest impact scores 100/-100 and the others relative to this (min-max approach) *Weighting:* The most important criterion is given the weight 1.0. The remaining weights are given relative to this and normalized.	*Local environment:* Surface water quality and quantity, groundwater quality and quantity, Air quality, Quality/structure of soil, habitat/ecology *Global environment:* Air quality (global warming), use of natural resources, waste production	Stakeholder acceptability	Harbottle et al. (2006): Financial costs (cost of remediation and change in estimated land value). Harbottle et al. (2008): Not included	Risk to site users, risk to public	*Site use:* Duration of remediation, impact on landscape, site use, surrounding land use	*2nd level criteria*
Rosén et al. (2009)	Sustainability assessment	Non-compensatory model combined with a linear additive model *Scoring:* -2 to 2. Negative score if there is a negative effect compared to initial situation. A sustainability index [-1;1] is calculated based on the 3 scores. *Weighting:* Equal weighting	Impacts on soil, groundwater, surface water, air, sediment. Use of natural resources	Justice and accept, Health (impacts from contamination, impacts from remediation), cultural environment, recreation and outdoor activities, area use (surroundings and on site)	Cost benefit analysis, methodology outlined in Rosen et al. (2008)			
GoldSET by Golder Associates (in Finn et al., 2011)	Sustainability assessment	Linear additive model. *Scoring*: 0-100 (Partly min-max approach) *Weighting*: Direct weighting between 1-3 for each 2nd level criteria	Soil quality, Sediment quality, groundwater quality, surface water quality, water usage, soil vapor intrusion, free product, drinking water supply, off-site migration, short and longterm impacts on habitat and/or land use, Greenhouse gas emission, energy consumption, wastes, hazardous wastes	Public safety, worker's safety, duration of work, quality of life (during the project), reuse of the property by the CN, use for the public, cultural heritage, local job creation & diversity, response to social sensitivity, standards, laws & regulations	Net present value of options' costs, potential litigation, financial recoveries, environmental reserve, train service reliability & performance, economic advantages for the local community, reliability (maintenance and repair), technological uncertainty			
Schädler et al. (2011)	Sustainability of different Brownfield land use distributions	Linear additive method *Scoring:* "True/false" statements translates into integer value pairs of +1/-1 or +1/0. *Weighting:* Direct weighting, case specific	Sustainable land management, Conservation of natural resources, Resource-conserving & emission-reducing mobility management,	High quality residential environment	Strengthening of local economy			*1st level criteria*
Balasubramaniam et al. (2007)	Involve stakeholders in decision process	Outranking (ELECTRE III) and linear additive model Scoring (linear additive model): -100 to 100 *Weighting (linear additive model)*: SWING method by email survey	Surface water quality, Groundwater quality, Air quality, Habitats and ecology		Financial impact on local residents	Health risks for site users, Health risks for the public		

Reference	Aim	Methodology	Environmental/ecological	Social/society	Economic	Human health	Other	
Sediment remediation								
Rogers et al. (2004)	Incorporating stakeholder values into decision process	Outranking (PROMETHEE)	Environmental quality, Impact on ecological habitat	Impact on human habitat	Cost per cubic yard			*1st level criteria*
Kim et al. (2010)		Linear additive model *Scoring*: 0-1 scale, min-max approach *Weighting*: Swing weighting	Ecological pathways, human health pathways	Social acceptability, remaining risk	Cost		*Technical:* Technical feasibility, project duration	
Sparrevik et al. (2011a)	Stakeholder involvement, Sustainability	Linear additive method Scoring: Linear relation between score and utility, not further explained *Weighting:* AHP (3-step scale), direct weighting	*Environment and health:* Environmental risk, human risk, greenhouse gas impact	Construction impact, disposal site location, marine archeology, land reclamation	Maximize governmental financing, maximize municipal financing			*2nd level criteria*
Water supply								
Lundie et al. (2008)	Sustainability assessment	Linear additive method *Scoring:* Min-max and ranges approach *Weighting:* Direct/AHP/SMART	Extraction of freshwater and groundwater resources, land use disturbance; Resource input; biodiversity, greenhouse gas emissions, eutrophication, photochemical oxidant formation, ecotoxicity (terrestrial, marine and freshwater)	Public understanding and awareness, affordability, employment, acceptability to community, distribution of responsibility, organizational capacity and adaptability	Life cycle costs (NPV)	Risk of infection, exposure to harmful substances	*Technical:* Performance potable water and wastewater quality, reliability, resilience/vulnerability, flexibility	
ASTA Decision Support System (Godskesen et al., 2011)	Sustainability assessment	Linear additive method Scoring: Score [0-1] based on the alternatives share of the total sum of indicator values for all alternatives *Weighting:* AHP, Rank Order Centroid and Rank Order Distribution	Total environmental impacts, toxic impacts, resource impact	Risks & safety, Customer values, applicability and demand	Benefit/cost ratio			

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