SCORE: Multi-Criteria Analysis (MCA) for Sustainability Appraisal of Remedial Alternatives

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ABSTRACT: For comprehensive and transparent appraisal of sustainability, multi-criteria analysis (MCA) is often suggested. Development of a relevant MCA-method requires consideration of a number of key issues, e.g. (a) definition of assessment boundaries, (b) definition of performance scales, both temporal and spatial, (c) selection of relevant criteria (indicators) that facilitates a comprehensive sustainability appraisal while avoiding double-counting of effects, and (d) handling of uncertainties. Adding to the complexity is the typically wide variety of inputs, including quantifications based on existing data, expert judgments, and opinions expressed in interviews. The SCORE (Sustainable Choice Of REmediation) MCA-method is developed to provide a transparent appraisal of the sustainability of possible remediation alternatives relative to a reference alternative, considering key criteria in the economic, environmental and social domains. The criteria were identified based on extensive literature studies and focus-group meetings. The economic domain has one key criterion: Social profitability, evaluated by cost-benefit analysis. The environmental domain criteria are: Soil, Surface water, Groundwater, Sediment, Air, Non-recyclable waste, and Non-renewable natural resources. The social domain criteria are: Local environmental quality & amenity, Cultural heritage, Equity, Health & safety, Local participation, and Local acceptance. SCORE combines a linear additive model to rank the alternatives with outranking to identify alternatives regarded as non-sustainable. The method is capable of integrating quantitative and qualitative estimations of criteria and provides a full uncertainty analysis of the results, using Monte Carlo simulation. Most importantly, it provides a structure that allows preferences and opinions of involved stakeholders to be openly integrated into the analysis.

INTRODUCTION

The main purpose of remediation of contaminated sites is to reduce negative impacts on humans and the environment. However, remediation also results in other effects of which some are positive and some are negative. For example, remedial actions are typically associated with high costs and their environmental footprints are sometimes significant compared to the reduction of environmental risks. At the same time, remediation may lead to positive social effects, e.g. improved recreation and local environmental quality.

The contradictory effects of remediation have received increased attention among decision-makers and various stakeholder groups over the last decade, see e.g. Bardos et al. (2011). A number of strategies and programs have been developed taking a more holistic view on remediation in order to provide for more sustainable remediation. The USEPA Green Remediation program (USEPA, 2012) was launched to establish relevant metrics and a methodology for evaluating the environmental footprint of remedial actions. The Sustainable Remediation Forum in the United Kingdom (SuRF UK, 2010; 2011) suggests a framework and indicators (criteria) for a comprehensive sustainability evaluation of remedial actions, considering positive and negative environmental, economic and social effects. The Network for Industrially Contaminated Land in Europe (NICOLE) also suggests a framework for sustainability assessment (NICOLE, 2012). During 2004-2009 the Swedish EPA (2009) performed a program comprising more than 50 projects on sustainable remediation. The International Standard Organization (ISO) currently works on a standard for sustainability evaluation of remedial actions.

As a result of the increased interest in evaluating the sustainability of remediation, a number of methods and tools have been described. Multi-criteria analysis (MCA) is increasingly used to provide support in environmental decision-making and for sustainability appraisal (see e.g. Belton and Stewart, 2002; Burgman, 2005; Hajkowitch and Collins, 2007; DCLG, 2009). The main idea of MCA is to assess the degree to which a project fulfils a set of performance criteria. A fundamental property of MCA is the ability to integrate different types of information into a comprehensive evaluation. MCA has been suggested for sustainability evaluation of remedial actions by a number of authors, e.g. Harbottle et al. (2008), Rosén et al. (2009), Linkov and Moberg (2011), and Brinkhoff (2011).

Development and application of MCA-methods face a number of challenges in order to provide model results that are relevant to the purpose of the analysis. Shortcomings often observed in MCA applications are the lack of uncertainty analysis, unclear definitions of system boundaries, dependencies between criteria resulting in double-counting of effects, and unclear definitions of performance scales (see e.g. Belton & Stewart, 2002).

The main purpose of this paper is to present the SCORE MCA-method, developed to provide a relevant and transparent appraisal of the sustainability of remediation alternatives relative to a reference alternative, considering key criteria in the economic, environmental and social sustainability domains. The method was developed considering the following key issues: (a) definition of assessment boundaries, (b) definition of performance scales, both temporal and spatial, (c) selection of relevant criteria for comprehensive sustainability appraisal while avoiding double-counting of effects, and (d) handling of uncertainties. The SCORE-method has been applied in a number of case studies in Sweden and Austria and an example is provided here to illustrate the use of the method.

THE SCORE METHOD

Sustainability. It was assumed that the sustainability of a remedial action can be relevantly assessed by evaluating its performances in the *economic*, *environmental* and *socio-cultural* domains, in line with the principles outlined in the Brundtland report *Our common future* from 1987. Each alternative is evaluated relative to a reference alternative by assessing the expected environmental, economic and social effects, using a set of criteria (indicators) in each domain. SCORE thus provides information of whether a specific remediation alternative *leads towards* sustainable development, taking the reference alternative as a point of departure.

SCORE identifies whether there is compensation between sustainability criteria or not and distinguishes between development towards *weak* and *strong* sustainability. Weak sustainability is defined as a non-decreasing total productive base over time, including components such as man-made capital (e.g. machines and infrastructure, natural capital (the environment and natural resources), human capital (health, knowledge, and skills), and social capital (relationships between individuals and institutions) (Arrow et al., 2003; Van den Bergh, 2010; Figge & Hahn, 2004). It builds upon the idea that the different types of capital contributes in a substitutable way to human well-being (Arrow et al., 2003; Bond & Morrison-Saunders, 2011). Weak sustainability might imply that irreversible impacts in the environmental, the social-cultural and the economic domains are neglected (Bond & Morrison-Saunders, 2011). Strong sustainability on the other hand, requires that each capital type is maintained separately (Van den Bergh, 2010).

Framework and general approach. The SCORE framework (Figure 1) was developed in in line with the view on decision support of e.g. Aven (2003).

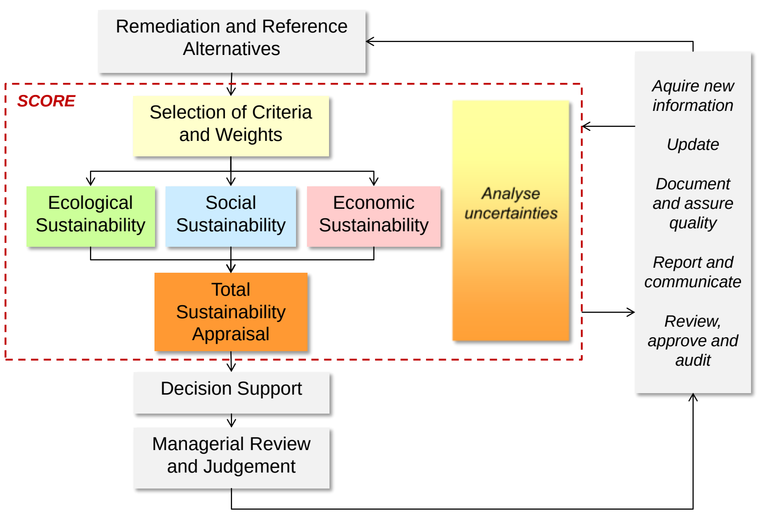


FIGURE 1. The SCORE framework

SCORE is designed to provide decision support when choosing between a set of remediation alternatives. The expected effects are represented by scorings in the environmental and social domains and quantifications of monetary costs and benefits in the economic domain. A normalized score is calculated for each alternative using a *linear* *additive approach*, taking into account scorings and quantifications of the criteria and the relative importance (weights) of these criteria. SCORE also uses *outranking* to distinguish between alternatives expected to lead to strong and weak sustainability, respectively (see e.g. Pearce et al., 2006). Uncertainty assessment is performed for each scoring and quantification, facilitating uncertainty and sensitivity analyses of the outcomes.

SCORE assesses whether a specific alternative is expected to *lead towards* sustainable development or not. It is also identifies possibilities on *how to improve* the sustainability of studied remediation alternatives. The method has an iterative approach, allowing for continuous updating as new information becomes available.

Conceptual model. According to Bardos et al. (2011), there are four types of boundaries that must be defined in order to perform a relevant sustainability assessment: (1) System boundaries, (2) Life Cycle Analysis (LCA) boundaries, (3) Temporal boundaries, and (4) Spatial boundaries. The boundaries must be defined with respect to the types of decisions the MCA is supposed to support.

The *system boundary* defines what parts/operations of the remediation project to include in the assessment, e.g. design, mobilisation, construction, production, maintenance, and utilisation. The *LCA boundary* defines how far a particular trail of impacts should be followed and to what level of detail (Bardos et al., 2011). For example, it should be clearly stated if impacts of the manufacturing of components like pipes and equipment should be included in the environmental domain or if they are considered to be outside of the boundary. The *temporal boundary* defines the time perspective applied regarding s e.g. long-term effects, short-term effects, effects during remediation, and/or effects after remediation is completed. The *spatial boundary* defines what locations and areas to include in the assessment, e.g. on-site effects only or also off-site effects.

A conceptual model was developed (Figure 2) to provide a relevant structure for the MCA, with proper consideration of the sustainability concept and providing possibilities for clear definitions of the boundary conditions. The conceptual model was developed according to the *cause-effect chain* concept commonly used in risk assessments. The *cause* of the effects is the remediation taking place at the particular site. The main *stressors* of the remediation is the change in *source contamination*, typically resulting in positive effects in terms of reduced risks to humans and ecosystems and possibilities for new land utilisation, and the *remedial action*, in some cases (not all) resulting in negative effects in terms of use of non-renewable energy, accidental risks, and air emissions. Effects associated with the change in the source contamination and the remedial action can take place at different *locations*, *on-site* and *off-site*. The *receptors* of the effects are humans and ecosystems. The main types of both *long-term and short-term effects* are environmental, economic and sociocultural effects.

The current system boundary of SCORE limits the assessment to a fixed future land-use scenario. The method can thus *not* be used in land-use planning for comparing e.g. the development of an industrial area into a residential area with the development of the same area into a recreational area. The user has to define in detail the system, LCA, temporal and spatial boundaries specific to each particular assessment.

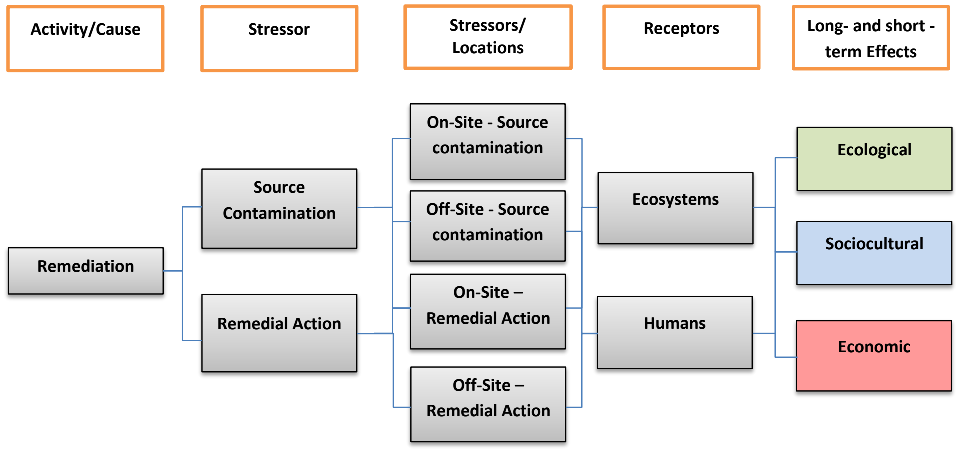


FIGURE 2. Conceptual Model

Criteria. According to e.g. Van den Bergh (2010) there are some critical aspects in each sustainability domain that cannot be substituted by others. Accepting this view, the purpose should be to select key performance criteria for each sustainability domain of the MCA, given the defined boundary conditions, which are mutually exhaustive and thus capable of collectively representing all critical sustainability aspects.

The selection of the key performance criteria was based on extensive literature review (Brinkhoff, 2011), several focus group meetings in Sweden, and an earlier prototype of the method (Rosen et al., 2009). The identified key performance criteria are listed in Table 1. The key criteria in the environmental and social domains have sub-criteria representing *on-site* and *off-site* effects as well as effects related to the change in *source contamination* and the *remedial action*, respectively.

TABLE 1. Key performance criteria for each sustainability domain in SCORE

Environmental domain	Socio-cultural domain	Economic domain
• Soil • Flora and fauna • Groundwater • Surface water • Sediment • Air • Non-renewable natural resources • Non-recyclable waste	• Local environmental quality and amenity • Cultural heritage • Equity • Health • Local participation • Local acceptance	• Social profitability

Sustainability Assessment. Options evaluated by SCORE must be specified by the user and all effects (impacts) are assessed relative to a reference alternative. It is up to the user to define the reference alternative but it is typically identical to the *no action* alternative, where no action is taken to reduce the risks to humans and the environment. The identified remedial alternatives must satisfy a number of constraints, mainly time, budget, technical feasibility, legal aspects, and public acceptability, see e.g. Bardos et al. (2001). Only remedial alternatives that meet the objectives within the constraints can be considered. The constraints are project specific and they are not part of the MCA.

Scoring of effects (criteria) is performed as follows: Very positive effect: +6 to +10; Positive effect: +1 to +5; No effect: 0; Negative effect: -1 to -5; Very negative effect: -6 to -10. The scoring procedure is supported by a guidance matrix for each criterion with examples and key questions to address. The scorings are performed using available data, expert judgment, questionnaires and interviews. The key criterion of the economic domain is social profitability assessed by means of cost-benefit analysis (Rosen et al, 2008). The main cost and benefit items are shown in Table 2. Several cost and benefit sub-items items are used for the CBA. The social profitability is calculated in monetary terms as a net present value (NPV) over the time horizon of the remediation project. In most cases all costs and benefits cannot be monetized and it is therefore important to also provide a qualitative discussion concerning items not quantifiable.

TABLE 2. Main cost and benefit items of SCORE

Benefits	**Costs**
B1. Increased property value on site	C1. Remediation costs
B2. Improved health	C2. Impaired health due to remedial action
B3. Increased provision of ecosystem services	C3. Decreased provision of ecosystem services due to remedial action
B4. Other positive externalities than B2 and B3	C4. Other negative externalities than C2 and C3

Each criterion in the environmental and sociocultural domains is weighted with respect to their relative importance. For each alternative *i* *(i*=1*…N)* a sustainability index *H* is calculated for each domain *D* as the weighted sum of the scorings for of the sub-criteria *j* *(j*=1*…M)*, using a simple linear additive approach:

$$H_{D,i} = \sum_{j=1}^{M} W_j K_j$$

The social profitability is quantified and no weighting is hence performed in the economic domain. A normalized sustainability score is calculated for each alternative *i* as:

$$H_i = 100\left(\frac{H_{E,i}}{Max\left[Max(H_{E,1..N})\,;\,\left|Min(H_{E,1..N})\right|\right]} + \frac{H_{S,i}}{Max\left[Max(H_{S,1..N})\,;\,\left|Min(H_{S,1..N})\right|\right]} + \frac{\Phi_i}{Max\left[Max(\Phi_{1..N})\,;\,\left|Min(\Phi_{1...N})\right|\right]} \right) \Big/ 3$$

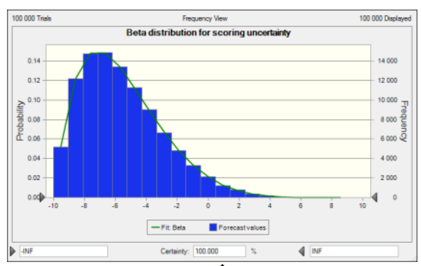
where *E* is the environmental domain, *S* is the sociocultural domain and Φ is the economic domain. The normalized score has a value between -100 and + 100, where a positive score indicates that the alternative leads towards sustainable development, i.e. more positive effects than negative. The normalized score can be used to rank the alternatives.

Uncertainty analysis. Scores and quantifications will always be associated with some uncertainty, i.e. the effects of the remedial alternatives can never be measured exactly. The uncertainty results from lack-of-knowledge (epistemic uncertainty) and natural variability (aleatory uncertainty). The former type of uncertainty can be reduced, at least in principle, but the latter is a result of the inherent randomness in nature. In addition, human subjectivity can result in different persons/groups assigning different scores to the criteria. A certain degree of subjectivity is unavoidable (Harbottle et al., 2008).

SCORE uses statistical distributions to represent the uncertainties in both scores and quantitative metrics. A conceptual description of the uncertainty representations of scorings is shown in Figure 3. The assignment of the uncertainty distribution is performed in three steps: (1) selection of distribution type, i.e. selection of whether all types of effects, only positive, or only negative effects are possible for the specific sub-criterion; (2) estimation of the most likely effect using the scale presented above; and (3) assigning the uncertainty level of the estimation of the most likely effect. The three-step procedure results in a beta probability distribution representing the uncertainty of the scoring of the sub-criterion.

The uncertainties of quantitative metrics of SCORE are represented by continuous statistical distributions. For example, lognormal distributions are used for most cost and benefit items in the economic domain.

- Distribution type
- Most likely effect (score)
- Uncertainty



		Alternative 1		
Key criteria	Sub-criteria	Dist Type	Effect	Uncertainty
E1: Soil	Ecotoxicological risk SC On-site A1	No negative scores possible	4	Low
	Ecotoxicological risk RA On-Site A1	No positive scores possible	-2	Medium
	Soil Functions RA On-Site A1	All scores possible	8	Low

FIGURE 3. Uncertainty representation of discrete scorings

EXAMPLE

SCORE is currently being tested at 5 sites in Sweden and Austria. An example of application at a former paint manufacturing industry is presented here. The site is located in the Gothenburg area of south-western Sweden and with a history of more than 100 years of paint production. The site is located in an area of complex glacial geology, including a terminal moraine deposit. Investigations and risk assessment of soil and groundwater showed unacceptable contamination risk levels for humans and ecosystems with respect to e.g. lead, softeners (DEHP), and poly-aromatic hydrocarbons (PAHs). The area is to be transformed into a residential area, so the increase in property value is expected to be substantial. To prepare for the construction of new buildings and infrastructure installations substantial amounts of soil had to be removed.

Four remediation alternatives were identified (Table 3), all including excavation and disposal. However, the alternatives differed with respect to the remediation goals and the technology used for pre-treatment of excavated soils.

TABLE 3. Remediation alternatives at the case study site

Alternative 1	Alternative 2	Alternative 3	Alternative 4
Excavation and disposal based on a generic risk assessment.	Excavation and disposal based on a site specific risk assessment.	Excavation, sieving and disposal based on a site specific risk assessment.	Excavation, sieving, soil wash and disposal based on a site specific risk assessment.

A SCORE analysis was performed on the four alternatives against a reference alternative, defined as continuous operation of the paint industry. Much of the fundamental work of the analysis was performed by Landström & Östlund (2011). Scorings in the environmental domain were based on site investigation and risk assessment reports. Social scorings were primarily based on stakeholder interviews. The CBA was performed in cooperation with project managers and local city representatives.

Figure 4 shows parts of the SCORE results. All alternatives performed well in the social domain. The most extensive remediation of the site (alternative 1) had a positive scoring in the environmental and social domains, but a negative social profitability due to high costs for disposal. The alternatives based on a site-specific risk assessment performed well in all three domains and better than alternative 1 in the environmental domain, due to less negative impacts from air emissions and waste generation. Alternatives with pre-treatment at the site (3 and 4) performed better in the environmental domain than the comparable alternative without pre-treatment (alternative 2). However, for the alternative including both sieving and soil washing (alternative 4) costs were significantly higher than for alternative 3 (sieving only), which made the final sustainability score lower. In total, alternatives 2, 3 and 4 showed a positive sustainability score in all three domains and therefore exhibit strong sustainability on the domain level. However, on the criteria and sub-criteria levels all alternatives show compensation between positive and negative effects, i.e. weak sustainability. Considering the uncertainties of the assessments, alternatives 2 and 3 are the ones showing the highest probabilities of being the most sustainable alternative. All alternatives show more positive than negative effects and most negative effects are off-site. Sensitivity analysis showed that the soil function performance, the property value increase and the remediation costs contributed most to the total uncertainty.

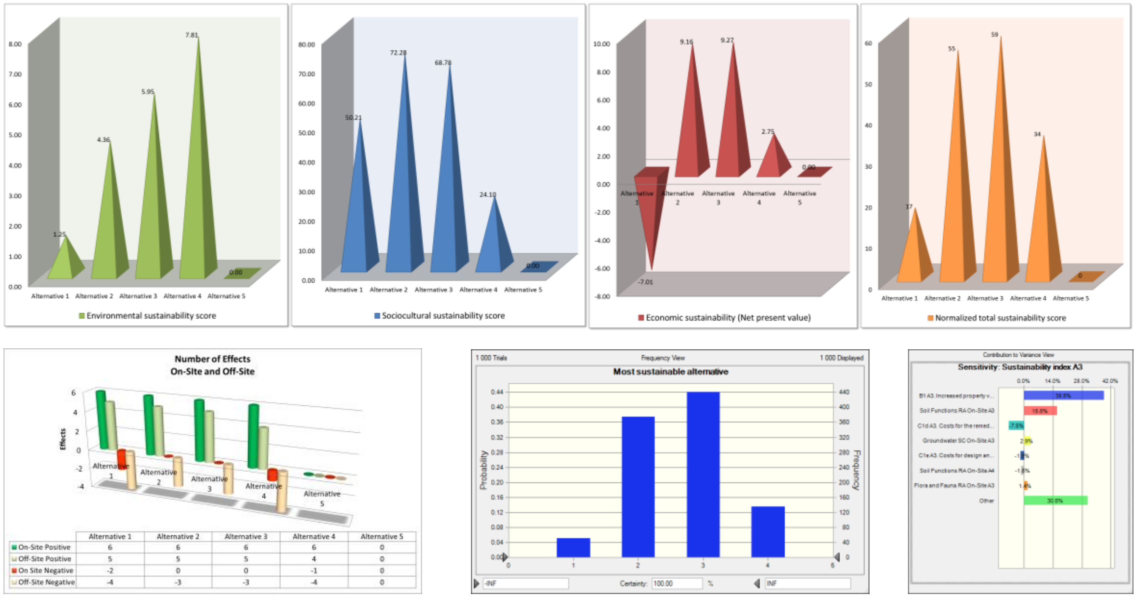


Figure 4. SCORE results - Environmental (upper left), Social (second upper left), Economic (second upper right), Total Sustainability (upper right), Number of positive and negative effects on-site, off-site, due to remedial action and due to reduction in source contamination (lower right), Probabilities of each alternative being the most sustainable (middle lower) and sensitivity analysis (lower right)

CONCLUSIONS

SCORE provides: (1) structure, transparency and decision support for identifying sustainable remediation alternatives and for increasing the sustainability of identified alternatives; (2) a means for integrating quantitative and qualitative information into a comprehensive sustainability assessment; (3) cost-benefit analysis of remedial actions, taking into account externalities such as effects on human health and provision of ecosystems services; (4) a means for including effects on soil functions and soil services in accordance with the upcoming EU Soil Directive; (5) an overview of positive and negative effects of remediation on- and off-site due to reduction of the source contamination and the remedial action itself; and (6) uncertainty analysis with e.g. information of the probability of each alternative being the most sustainable and where to focus for achieving a more reliable sustainability appraisal. Finally, despite the substantial amount of results produced by SCORE, its most important contribution may be that it initiates a process where criteria otherwise likely ignored are addressed and openly discussed between stakeholders.

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