THESIS FOR THE DEGREE OF LICENTIATE OF ENGINEERING

Economic Project Risk Assessment for Sustainable Choice Of REmediation (SCORE) in Construction Projects

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ABSTRACT

Contamination of soil and/or groundwater is a problem all over the world. There is a desire from politicians and the supervisory authorities to tackle the contamination problem in order to protect future generations. Remediation, in the past considered sustainable in itself has in recent years been debated in regard to the possible negative effects such as greenhouse gas, dust emission, waste generation and risks of traffic accidents. Construction companies come into contact with contamination in various kinds of projects, e.g. construction of houses, roads and bridges. Remediation projects are high-risk projects due to the many uncertainties regarding issues such as scope, quality, time and cost and an inability to handle them. This thesis presents a Project Risk Assessment (PRA) method, based on the established ISO standard of risk management, developed for project owners, e.g. construction companies. The method identifies, quantifies, analyses and evaluates project risks in remediation projects. The suggested method is probabilistic and includes uncertainty analysis of input variables based on expert judgment. A stepwise procedure and a computer based tool (PRA tool) were developed to facilitate the project risk assessment.

The PRA method was developed within a sustainability assessment framework called SCORE (Sustainable Choice Of REmediation), but is also viable as a standalone tool for remediation projects. Assessment of project risks in monetary terms is part of a company's financial analysis and in SCORE it is included in the economic domain as part of a cost-benefit analysis (CBA) of societal profitability. PRA and SCORE are in line with current trends and work on sustainability in construction companies, such as the use of certification systems like BREEAM, LEED and CEEQUAL. The PRA method is applied on a case study: an old paint factory which is being redeveloped into a residential area. The result of the case study application shows which alternative has the lowest mean risk cost, the highest probability to have the lowest risk cost and how the risk costs are distributed among the project risk categories. In addition, most importantly, helps the user to prioritise between risk-reducing measures. The PRA is a structured and transparent method for handling project risks and an important part of a sustainability assessment of remediation alternatives. It is beneficial to the risk management team in remediation projects and could in the future advantageously be further developed for use in larger infrastructure projects.

Keywords: probabilistic risk analysis, construction companies, project risk assessment, cost-benefit analysis, sustainability assessment

Ekonomisk projektriskanalys vid val av hållbar sanering (SCORE) i byggprojekt
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SAMMANFATTNING

Förorening av jord och grundvatten är ett problem över hela världen. Det finns en önskan från politiker och tillsynsmyndigheterna att angripa föroreningsproblematiken för att skydda framtida generationer. Sanering, som tidigare ansetts vara hållbar i sig självt har under de senaste åren debatterats om att det finns negativa bi-effekter såsom spridning av växthusgaser, dammutsläpp, avfall och risker för trafikolyckor. Byggföretag komma i kontakt med föroreningar i olika typer av projekt, t.ex. byggande av hus, vägar och broar. Saneringsprojekt är högrisk projekt på grund av de många osäkerheterna när det gäller frågor som omfattning av föroreningen, kvalitet på saneringsalternativet, tid och kostnad och det finns generellt en oförmåga att hantera dessa osäkerheter. Denna avhandling presenterar en metod för projektetriskbedömning (PRA) baserat på etablerade ISO-standarden för riskhantering, utvecklad för projektägare, t.ex. byggföretag. Metoden identifierar, kvantifierar, analyserar och utvärderar projektrisker i saneringsprojekt. Den föreslagna metoden är probabilistisk och inkluderar osäkerhetsanalys av de ingående variablerna baserat på expertutlåtanden. Ett stegvis förfarande och ett datorbaserat verktyg (PRA tool) har utvecklats för att underlätta riskbedömningen i projekt.

Denna PRA metod utvecklades inom ett ramverk för bedömning av hållbarhet som kallas SCORE (Sustainable Choice Of REmediation), men fungerar också som ett fristående verktyg för saneringsprojekt. Bedömning av projektrisker i monetära termer är en del av ett företags finansiella analys och i SCORE ingår det i den ekonomiska domänen som en del av en kostnadsnyttoanalys som beräknar samhällelig lönsamhet. PRA och SCORE är i linje med aktuella trender och arbetet med hållbarhet i byggföretag, som t.ex. användningen av certifieringssystem som BREEAM, LEED och CEEQUAL. PRA metoden tillämpas på en fallstudie: en fastighet där det legat en färgfabrik sedan länge. Fastigheten planeras att omvandlas till ett bostadsområde. Resultatet av fallstudien visar vilket alternativ som har den lägsta genomsnittliga riskkostnaden, den högsta sannolikheten att ha den lägsta riskkostnaden och hur riskkostnaderna fördelas mellan projektriskkategorierna. Dessutom hjälper metoden framförallt användaren att prioritera mellan riskreducerande åtgärder. PRA är en strukturerad och transparent metod för hantering av projektrisker och en viktig del av en hållbar bedömning av saneringsalternativ. Det finns stora fördelar för ett riskhanteringsteam i ett saneringsprojekt att använda metoden och i framtiden kunde man med fördel vidareutveckla metoden för användning i större infrastrukturprojekt.

Nyckelord: probabilistisk riskanalys, byggföretag, projektriskbedömning, kostnadsnytto analys, hållbarhetsbedömning

LIST OF PAPERS

This thesis includes the following papers, referred to by roman numerals in the text.

I. Brinkhoff P, Norin M, Norrman J, Rosén L, Ek, K. (2014). Economic project risk assessment in remediation projects prior to construction - Methodology development and case study application, Manuscript submitted to *Remediation Journal.*

II. Söderqvist, T., Brinkhoff, P., Norberg, T., Rosén, L., Back, P-E., Norrman, J. (2014). Cost-benefit analysis as part of a sustainability assessment of remediation alternatives for contaminated land, Manuscript submitted to *Journal of Environmental Management.*

III. Rosén, L., Back, P-E., Söderqvist, T., Norrman, J., Brinkhoff, P., Norberg, T., Volchko, Y., Norin, M., Bergknut, M., Döberl, G. (2014). SCORE: Multi-Criteria Decision Analysis for Assessing the Sustainability of Remediation at Contaminated Sites, Manuscript submitted to *Science of the Total Environment.*

Division of work between authors:

Brinkhoff initiated Paper I and developed the PRA method together with Norin and Rosén. Brinkhoff performed calculations and simulations. All authors reviewed the text. Brinkhoff was the main author of Paper I.

In Paper II, Brinkhoff has contributed with text on the Hexion case study and information about project risks. Brinkhoff also contributed with input to the calculations and simulations on the case study, Hexion. Brinkhoff has also done a literature search on the use of CBA in remediation projects and reviewed the text in the paper. Söderqvist is the main author of Paper II

Rosén is the main author of Paper III. The presented SCORE method is based on the conjoint work of the research group reflected in the author list. Brinkhoff has worked on the development of key and sub-critera and the guiding matrix. Brinkhoff also contributed in regard to the case study Hexion.

Publications not appended

The following publications are not appended but were written within the framework of the project.

IV. Rosén, L., Norrman, J., **Brinkhoff, P**., Norin, M., Back, P-E., Norberg, T., Söderqvist, T.(2010). *SCORE: Multi-Criteria Analysis for Evaluating Sustainable Remediation Alternatives in the Built Environment*, abstract and poster presentation, NORDROCS, Copenhagen, Denmark, September 15-16, 2010.

V. **Brinkhoff, P**., Norrman, J., Rosén, L., Norin, M. (2011). Development of sustainability criteria for remediation of contaminated land in construction projects, abstract, oral presentation by Brinkhoff, Amherst, MA USA, June 1-3, 2011.

VI. **Brinkhoff, P**. (2011). Multi-Criteria Analysis for Assessing Sustainability of Remedial Actions-Applications in Contaminated Land Development, A literature Review. Gothenburg, Chalmers University of Technology, Department of Civil and Environmental Engineering, Division of Geo Engineering.

VII. Norrman, J., Volchko, Y., Rosén, L., **Brinkhoff, P**., Norin, M., Söderqvist, T., Kinell, G., Norberg, T. (2012). Development of a tool for evaluating the sustainability of remediation alternatives. In *Proceedings of the 16th Nordic Geotechnical Meeting*. Copenhagen, Denmark, May 9-12, 2012. Vol.2/2, dgf-Bulletin 27, 793-800.

VIII. **Brinkhoff, P**., Norin, M. (2012). Assessment of economic consequences of project risks in remediation of contaminated land. *The 2nd International Conference on Sustainable Remediation*, abstract, oral presentation by Norin Vienna, Austria, November 14-16, 2012.

IX. Rosén, L., Back, P-E., Norrman, J., Söderqvist, T., Norberg, T., Volchko, Y., **Brinkhoff, P**., Norin, M., Bergknut, M., Döberl, G. (2013). SCORE: Multi-Criteria Analysis (MCA) for Sustainability Appraisal of Remedial Alternatives. In *Proceedings of the Second International Symposium on Bioremediation and Sustainable Environmental Technologies*, June 10-13, 2013, Jacksonville, Florida, USA.

X. Ek, K., **Brinkhoff. P.** (2013). Hållbarhetscertifiering med CEEQUAL i Sverige – Två fallstudier. SBUF-rapport ID: 12609.

XI. **Brinkhoff, P**., Ek, K., Norin, M. (2013). Sustainability assessment of the redevelopment of Hexion with CEEQUAL. NICOLE Network meeting and workshop, June 13-14, 2013, abstract, short paper and oral presentation by Brinkhoff.

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Sincere thanks to my colleagues at the Division of GeoEngineering and at *NCC Teknik och Hållbar Utveckling* for their support and encouragement. Special thanks to Kristine Ek for patiently awaiting my return to our shared office and projects.

Thanks to my parents and sisters for believing in me and encouraging me to keep moving forward. A special thanks to mum for caring for me and my daughters more than I could ever have expected. A special thanks to Ylva, Nette and Anna – my sisters in life if not by blood – for being part of my life.

Moa and Miriam, you are the love of my life. I could not have finished this work without you. You are the most loving and supportive daughters anyone could ask for and you are truly the best people in the whole world.

Gothenburg, October 2014

Petra Brinkhoff

TABLE OF CONTENTS

LIST OF NOTATIONS

Abbreviations

BREEAM	British Research Establishment Environmental Assessment Method
CBA	Cost-benefit analysis
CEA	Cost-effectiveness analysis
CEEQUAL	Civil Engineering Quality Assessment and Awards Scheme
DST	Decision support tool
EC	Environmental Code
GHG	Greenhouse gases
LEED	Leadership in Energy and Environmental Design
MCA	Multi-criteria analysis
MCDA	Multi-criteria decision analysis
NPV	Net Present Value
PBA	Plan and Building Act
PRA	Project risk assessment
PV	Present value
SEPA	Swedish Environmental Protection Agency
SGBC	Sweden Green Building Council
SUNRA	Sustainability for National Road Administrations

1. INTRODUCTION

This first chapter introduces the context of the thesis by providing the background to the research, defining the aim and objectives and presenting the scope of the work.

1.1 Background

A large number of the approximately 80,000 potentially contaminated sites in Sweden are located in an urban environment and are often former industrial sites. The situation is similar throughout the rest of Europe and in the USA. Soil and/or groundwater remediation are required on these sites in order to reach acceptable levels of risk to human health and/or the environment or as part of a change in land use. Construction companies are an important driver in changes in urban land development when constructing, for example, houses on formerly contaminated land. The state and the authorities mainly initiate remediation work based on political environmental goals or legislation Nordin (2014). According to the Swedish EPA, remediation projects initiated as a result of the development of land and those initiated by the supervisory authorities on the basis of the Environmental Code and/or through state funding are about the same in number (Nordin, 2014). However, there is probably a large underestimation in the number of remediation measures initiated as part of redevelopment projects since not all measures are reported to the regional authorities.

Remediation work has traditionally been viewed as a sustainable activity *per se* (Bardos, 2009). However, during the last decade a debate has emerged among remediation experts, scientists and authorities in which this is being questioned since remediation activities may give rise to negative effects (Vegter et al., 2002; Bardos et al., 2011; SEPA, 2009a). Examples of such negative effects are emissions of greenhouse gases, production of waste for disposal, high energy consumption, use of non-renewable resources and dust generation. Moreover, remediation projects are associated with a risk of traffic accidents due to transport and of injury at the remediation site. Other risks are acute contamination risks during remediation as well as long-term environmental risks at the disposal site.

The construction industry is one of the most energy-intensive sectors and at the same time it generates a large amount of waste (Ding, 2008). It is a challenge to change this course and become, for example, less energy-intensive. This task has been embraced by construction companies. A number of initiatives have been launched internationally and in Sweden with the aim is to minimise the negative impact of civil engineering and housing projects and thus attempt to be more sustainable. Examples are the development and implementation of environmental certification systems for housing (Ding, 2008) and a project aiming at investigating the sustainability of the civil engineering sector in Sweden (HIA), financed by the Swedish Building Industries Development Fund (SBUF), i.e. research and development cooperation between construction companies in Sweden.

Assessment of the environmental sustainability of construction projects is performed mainly using point score methods (systems) such as BRE

Environmental Assessment Method (BREEAM), Leadership in Energy and Environmental design (LEED) (Surf-UK, 2010), and Greenbuilding. In Sweden these systems are managed by the Sweden Green Building Council (SGBC). SGBC also manage the Swedish system Miljöbyggnad (SGBC, 2014). Systems for civil engineering projects are e.g. the Civil Engineering Environmental Quality Assessment and Awards Scheme (CEEQUAL) (CEEQUAL, 2012). Methods like these evaluate the degree, expressed as a percentage of the total score, to which a project, i.e. a deliverable product, fulfils a set of sustainability criteria. Hence, these methods do not aim to provide decision support by comparing the sustainability of different alternatives (Ding, 2008). In situations where that is the aim, there is a lack of tools and methods.

In this thesis the term construction project is used for projects that construct buildings and other type of constructions such as bridges as well as for ground work such as building roads and remediation which is more commonly termed civil engineering work.

Figure 1.1 shows a jigsaw puzzle representing construction projects that take the three domains of sustainability into account. Remediation can be part of broader sustainability work where, for example, CEEQUAL, BREEAM or another certification system is used. As part of the broader construction work it is crucial that all the individual elements are as sustainable as possible to ensure a sustainable construction project. Hence, material use, costs, project risks and the historic environment need to be considered for all the contributing parts of the construction project, such as remediation. Remediation projects can also be viewed as construction projects *per se* and as such all domains of sustainable development need to be assessed in order to achieve sustainable remediation.

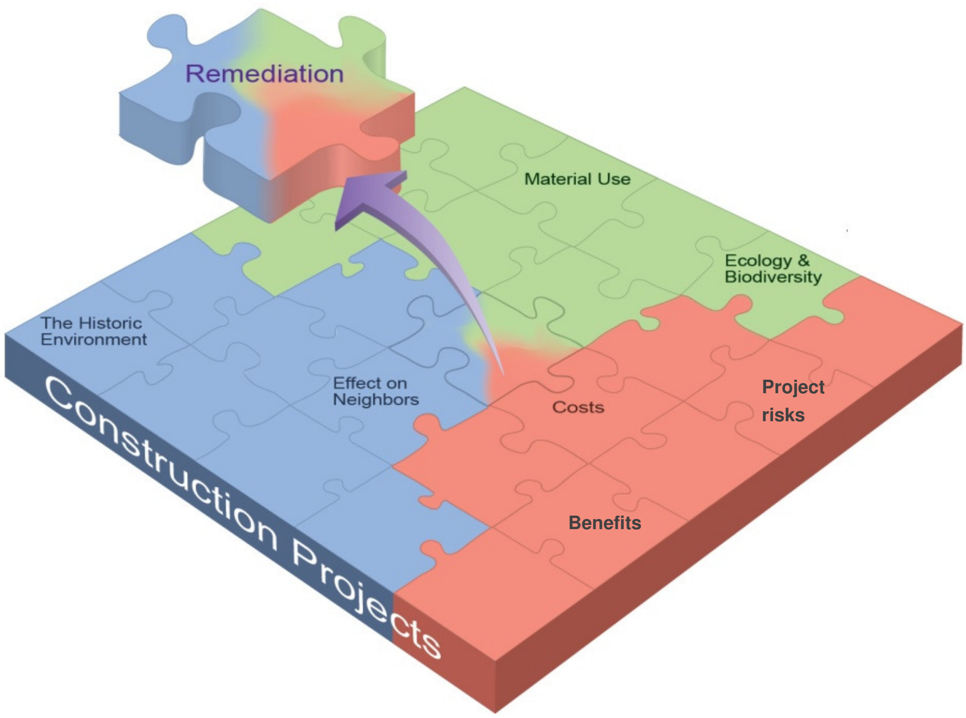


Figure 1.1 *Remediation as part of broader sustainability work at the construction company.*

Today there is no single accepted method or tool for sustainability assessment of remediation alternatives (Brinkhoff, 2011). Several approaches, e.g. Life Cycle Analysis (LCA), Cost-Benefit Analysis (CBA) and Cost-Effectiveness Analysis (CEA), have been suggested in the literature (e.g. SURF-UK, 2010; Onwubuya et al., 2009; Bello-Dambatta et al., 2009). Multi-Criteria Analysis (MCA) or Multi-Criteria Decision Analysis (MCDA) have been used previously for research and 'real' clean-up purposes in order to evaluate and compare the sustainability of remediation alternatives (e.g. Postle et al., 1999; Ritchey, 2008; Harbottle et al., 2008; Sorvari and Seppälä, 2010; Bello-Dambatta et al., 2009). The consensus is that MCDA enables an integrated assessment to be made of nature-society systems in a single evaluation (Ness et al., 2007; SURF-UK, 2010). Examples of Decision Support Tools (DST) on the market that are based on MCDA include GoldSet© and Samla (Witton, 2009; SGI, 2014).

The Swedish EPA (SEPA, 2009a) suggests MCDA to be a suitable approach for assessing remediation alternatives. Rosén et al. (2009) developed an MCDA prototype method within the 'Sustainable Remediation' knowledge programme run by the Swedish EPA during the period 2006-2008. This prototype has been further developed into SCORE (Sustainable Choice Of REmediation), which is included in this thesis (Rosén et al., 2014; Paper III).

SCORE integrates social and environmental analyses of remediation alternatives with a fully quantitative economic analysis and it evaluates remediation alternatives in terms of strong and weak sustainability on both the sustainability domain and criteria levels. SCORE also allows weighting of sustainability domains and criteria, provides a gross set of non-overlapping key performance criteria and provides a full uncertainty analysis of the outcomes. All these parts are combined into one single method. The sustainability of the economic dimension is evaluated using CBA from a societal perspective. One of the four main cost item groups in the CBA is related directly to costs for the project owner, and includes costs for unexpected events, i.e. financial project risks. In the context of a SCORE sustainability assessment, project risks are included in the economic sustainability domain of remediation, see Söderqvist et al. (2014; Paper II). Being a part of a CBA, which has a broader societal scope than a financial analysis, the PRA is denoted by the more general term *economic project risk assessment* in this thesis. .

The remediation technique most commonly used in Sweden, and in many other countries, is excavation combined with disposal (Ländell, 2012). Excavation and disposal may not be sustainable due to high costs, substantial emissions of greenhouse gases from transport, the generation of large amounts of waste, the use of non-renewable resources and noise and dust problems during operation. There are many reasons for the extensive use of excavation. For the supervisory authorities in Sweden, the environmental quality objective 'A non-toxic environment' has a strong impact on remediation work. This is leading to the prioritisation of removal of contaminants by excavation rather than other forms of risk mitigation.

Construction companies also tend to use excavation due to time constraints and so on, reflecting an unwillingness to tie up capital in a project over a long period. Other reasons are that excavation is often necessary to make room for construction on a site. There is a perception that excavation reduces project risks that could result in costly delays, such as failure to achieve acceptable health and environmental risk levels. Limited knowledge about how effective alternative methods are is probably also a reason for the extensive use of excavation and disposal (Ländell et al., 2012; Rosén et al., 2014).

However, excavation and other remediation techniques are associated with substantial project risks. These can take the form, for example, of uncertainty on the contamination level or the volume of contaminated soil, which might affect the budgeted cost by needing to add costs for excavation, transport and disposal (Tilford et al., 2000; Lemetrie, 2013). According to Havranek (1999) and Diekmann (1997), the reasons for cost increases derive from uncertainty in scope, quality of performance/technology, time, and cost (expected/budgeted). They also point out that the insufficiency of the project team to manage these uncertainties is the reason why project costs increase and time delays occur.

Risks like project risks are commonly defined as the probability of an unexpected event occurring and the consequence if it does. Project risk assessment in soil remediation projects prior to construction commonly involves a qualitative or semi-quantitative assessment of probabilities and consequences for predetermined categories of risks and possibilities see e.g. Government of Canada (Gov. Canada, 2014; Ottosson, 2009). A semi-quantitative analysis can be used to make a rough assessment of the risk cost level by using fixed ranges of probabilities and economic consequences. A more recent publication by Wolf et al. (2012) states that the uncertainties associated with remediation projects still exist and need to be managed.

Remediation projects can thus be viewed as high-risk projects due to the many uncertainties (Wolf et al., 2012). Havranek (1999) concludes that for the purpose of risk management, one way to handle these uncertainties is to express the impact on remediation scope, quality and time in monetary terms by, for example, making an advanced economic project risk assessment, i.e. i.e. quantitative decision analysis based on a quantification of the probabilities and consequences of unexpected events, with the possibility of including uncertainties in probabilities and consequences. Several other authors present risk cost analysis methods for use in remediation projects, see Lemetrie (2013), Diekmann (1997) and Diekmann and Featherman (1998) and Morse (1993).

However, the project risk assessment approach of combining quantitative risk analysis with uncertainty assessment of input variables (Probability and Consequence), does not seem to be as widespread in the remediation sector as in other sectors. In the nuclear and chemical processing sector (Bedford and Cooke, 2001) and in oil and gas exploration (Havranek, 1999) such methods are common.

Evaluation of potential project risk costs fits into the company's financial analysis and thus into the economic domain of a sustainability analysis (see also Figure 1.1). Sustainability analyses, including project risk assessments, are also beneficial from a business perspective since such analyses can raise the company's profile on the market while at the same time allowing them to acquire efficiency advantages by taking project risks into account.

1.2 Aim and objectives

The overall aim of the thesis is as follows:

> *To develop a method for economic project risk assessment (PRA) of remediation measures from a project owner's perspective (e.g. the construction company), with the purpose of managing project risks and allowing the inclusion of project risks in sustainability assessments of alternative remediation measures in the SCORE framework.*

In addition to the overall aim, the thesis has the following specific objectives:

- Identify project risk categories related to remediation in construction projects that are relevant to the project owner.
- Develop a computer-based PRA tool to facilitate economic project risk calculations marked by uncertainty.
- Show a viable example of the PRA method, complete with applications and illustrations, by performing and presenting a case study.
- Show how the PRA results are an integral part of the CBA and the SCORE assessment.

The definition of project risks used in this thesis is:

> "*A project risk is the product of the probability that an unexpected event will occur while carrying out a specific remediation alternative and the economic consequence of that event for the construction project owner. The probabilistic risk cost is thus a possible but unexpected additional cost and not a result of the uncertainties of expected costs, i.e. budgeted costs.*" *(*Brinkhoff et al., 2014; Paper I).

1.3 Scope of the licentiate work

Chapter 1 of this thesis presents the background, aim and objectives. Chapter 2 provides an overview of the research projects, professions and working procedures that have interacted in the development of the SCORE method and tool for sustainability assessment of remediation alternatives. The PRA in the context of the economic domain for sustainable remediation assessment (SCORE) is also presented in this chapter. Chapter 3 provides an overview of the construction processes, detailed development plan process, remediation prior to construction and associated project risks and project risk management.

Chapter 4 contains an elaboration on the concept of sustainable remediation, assessment methods for sustainable remediation, and other types of sustainability (and environmental) assessment methods linked, for example, to the construction of houses. Chapter 5 presents the concept and general principles of the SCORE sustainability assessment method and the CBA in SCORE. Chapter 6 contains a description of the methods used in this thesis to develop the PRA methodology and tool. The results, i.e. the methodology and tool, are described in Chapter 7.

The application of the PRA method and the SCORE tool to a case study is presented in Chapter 8. The outcomes of the thesis are discussed in Chapter 9 and the conclusions are presented in Chapter 10.

A literature review (Brinkhoff, 2011) dealing with MCA for assessing sustainability of remediation measures and applications in contaminated land development were conducted within the framework of the research. The review describes, for example, the concept of sustainable development, MCDA methodologies, remediation techniques, sustainability assessment using MCA or MCDA and applications in remediation projects. The literature review provides the basis for parts of Chapters 3 and 4 of this thesis.

Paper I deals with the economic assessment of the project risks when remediation is performed prior to or as part of a construction project. The paper describes the background to the development of the PRA method, the associated computer tool and the application to a case study site, Hexion. Paper I provides the basis for parts of Chapters 3, 6, 7 and 8 of this thesis.

Paper II deals with the economic assessment (CBA) of the sustainability tool SCORE and the theoretical foundations of the economic assessment. The paper also presents detailed results of the economic assessment for the Hexion site. Aspects of economic assessment and the use of CBA in sustainability assessments are included in Chapter 5 of this thesis.

Paper III is a comprehensive paper that also presents underlying theoretical positions regarding the sustainability assessment of remediation alternatives in the environmental, social and economic domains. Paper III presents a detailed description of the concepts and principles of the SCORE sustainability tool. SCORE's structure and functions are also presented. An overview of SCORE is given in Chapter 5. The fundamentals of the need for a tool such as SCORE are included in Chapter 4.

2. OVERVIEW OF THE RESEARCH ORGANISATION

This chapter provides an overview of the research organisation, of which the research presented in this thesis is part of.

2.1. Research projects

During the period 2009-2014 five parallel research projects were conducted, each with individual objectives and scope but with the common overall aim of developing a sustainability assessment method for the sustainable choice of remediation alternatives. These five research projects are:

Project 1: Sustainable remediation prior to building on contaminated sites. Funded by the Swedish Building Industries Development Fund (SBUF), NCC and Chalmers University of Technology.

Project 2a: Sustainable and cost-effective remediation of contaminated sites in the built environment. Funded by Formas-BIC, NCC, Chalmers University of Technology and Enveco.

Project 2b: Decision support for sustainable remediation in urban areas. Funded by Formas.

Project 3: Multi-criteria analysis of remediation to assess its overall impact and cost/benefit with focus on soil function and sustainability. Funded by the EU (SNOWMAN). A collaborative venture between Umeå University (MCN) and the Environment Agency Austria.

Project 4: Multi-criteria analysis for identification of sustainable remediation alternatives. Funded by Formas and through cooperation between Umeå University (MCN), NCC and Enveco.

As a result of the interaction between the different projects, the SCORE sustainability assessment method and tool was developed, see Figure 2.1. Methodology development took place mainly in projects 1 and 2. SCORE includes several components, and the other projects contributed with special input in terms, for example, of soil function assessment, environmental risk assessment and a European perspective on soil remediation. Soil functions and the link to sustainable remediation were the main research focus for projects 3 and 4.

At the beginning of the research period several tasks were performed in project 1 to support the development of the SCORE method and tool. These tasks were a) a literature study dealing with MCA and sustainable remediation, and b) an inventory of criteria linked to assessment of sustainability in remediation projects.

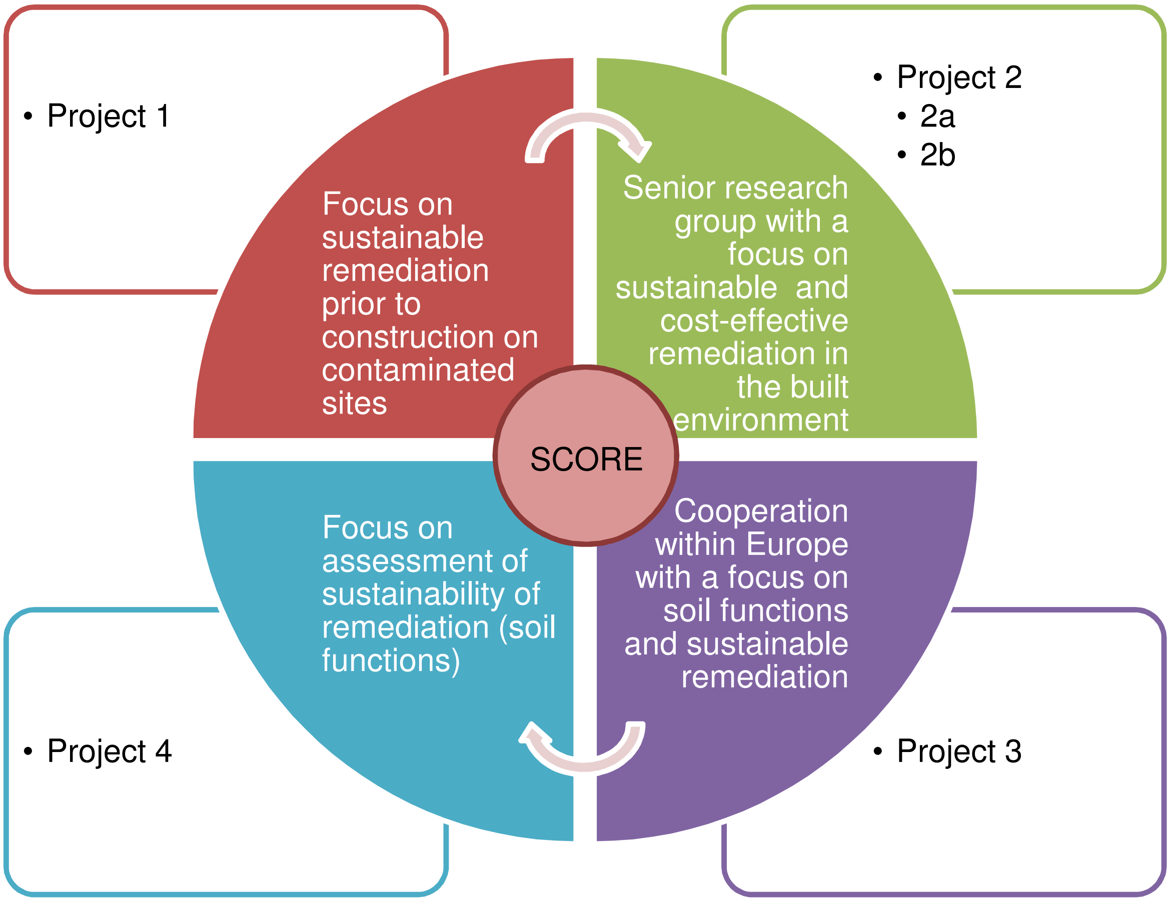


Figure 2.1 Interactions between the five research projects to develop SCORE.

2.2. Research and development environment

The individual research projects interacted over the years in several activities that contributed to the development of different concepts of sustainable remediation as well as the overall development of the SCORE sustainability assessment tool. The following activities were conducted:

- Working meetings
- Joint seminars
- Joint case study areas
- Joint conference attendence and presentations
- Joint papers and reports

The research projects had a varied member composition, resulting in interdisciplinary as well as transdisciplinary collaboration and an exchange of experience and knowledge of remediation work between the different collaborators. The following experiences and affiliations formed part of the research:

- Risk assessment specialists
    - Academia, consulting firm, research institute
- Statistics specialist
    - Academia
- Environmental economist
    - Consulting firm
- Remediation experts
    - Construction company, Environmental Protection Agency of Austria (Umweltbundesamt)
- Social impact assessment
    - Academia, consulting firm
- Multi-criteria analysis
    - Academia

The diversity of the projects and research team members provided synergies for the development of the various methods. The CBA, the PRA, the soil function assessment method (Volchko, 2014), the procedure for social impact assessment and the method for joint uncertainty analysis of scores and quantitative metrics in multi-criteria decision analysis are all integral parts of the final SCORE method. Some of these methods, such as the PRA, can also be used as stand-alone methods. The focus group sessions involving the general public and authorities (Norrman and Söderqvist, 2013), the literature reviews and the expert interviews during the workshops, provided a necessary basis for the development of these methods. The testing of the developed methods in real-world case studies facilitated adaptation of the various methods for practical applications.

2.3. Project risk assessment as part of SCORE

The suggested PRA method described in this thesis provides input for the CBA of the economic domain in the SCORE sustainability assessment tool, which is described briefly in Chapter 5 of this thesis. The cost items in the CBA are divided between costs for the contractor and costs for society. The suggested PRA method facilitates estimations of project risks included in contractor costs. Figure 2.2 shows how project risks are an integral part of SCORE. For an in-depth description of SCORE and the CBA method in SCORE, see Rosén et al. (2014) and Söderqvist et al. (2014).

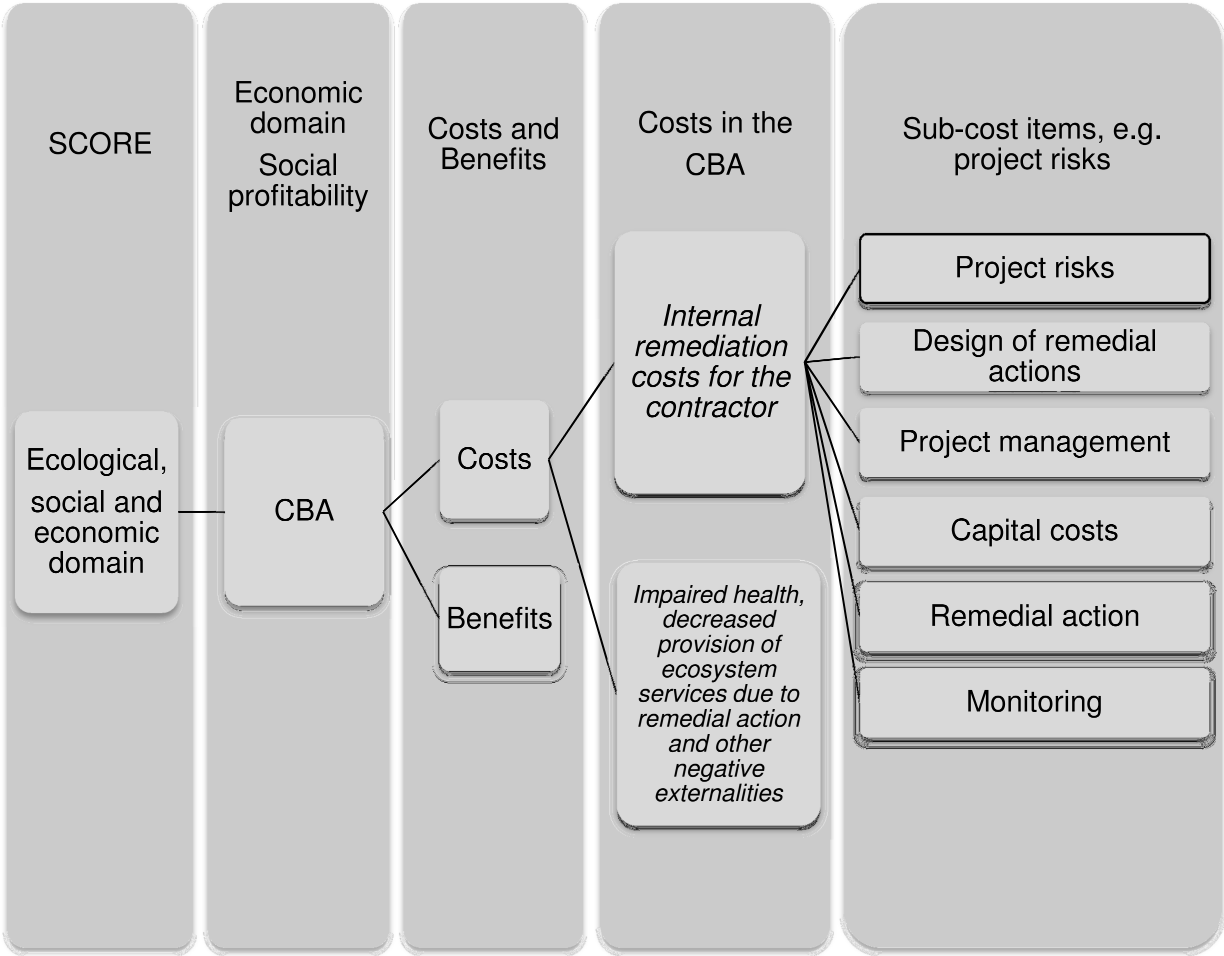


Figure 2.2 Project risks as part of the SCORE method.

3. CONSTRUCTION ON CONTAMINATED SITES

This chapter provides an overview of construction processes and the different contract forms used in construction projects. The chapter also elaborates on when, how and what legal aspects are linked to remediation prior to construction. It is also discussed how and when the municipal planning process and remediation projects meet and how they interact. This chapter puts project risks in construction projects in context.

3.1. Construction processes

Construction projects, i.e. construction of houses, bridges and road constructions, etc., often involve dealing with contaminated soil and/or groundwater. Within these projects, issues often arise with regard to the management of contaminants. The management process may differ depending on the type of project. Regular civil engineering work for example does not necessarily extend over a long period compared to housing projects. This can, for example, affect the remediation project with regard to the amount of money available for remediation, as well as the design, the remediation measures and the remediation objectives. The descriptions in the sections below focus on Swedish conditions.

Housing and property development

Larger construction companies often have a department responsible for buying and selling properties. Typically, another department develops residential properties, office buildings and other commercial buildings. Sometimes a remediated property is sold with new housing but sometimes without. It is land located near the city centre and close to transport links that is sought (Bengtsson, 2010). In metropolitan regions today, these sites are commonly on former industrial land that has been contaminated to a varying degree as a result of former industrial activity at the site and/or from filling with contaminated material (NICOLE, 2012).

In the initial stage, when a number of land areas of interest have been identified, an investment estimate is made. Such an estimate shows the cost to buy the land and the possible selling price with buildings on it (willingness to buy and willingness to pay by future owners). The investment calculation then proceeds to the next stage, where the items that are economically viable are identified. After that stage soil conditions, including contamination and possible remediation work are taken into account (Bengtsson, 2010).

Procurement and tender process in civil engineering projects

Construction in civil engineering projects is often preceded by a procurement process. This is where the client states what they want the contractor to deliver and the contractor calculates a price for the job. In the case of private procurement, price is not always the most important criterion.

Figure 3.1 shows the procurement process for civil engineering projects from a client and contractor perspective. The three most common forms of construction contracts are shown – general, turnkey, and build and operate contracts. Partnering also occurs in construction with the aim of achieving shared responsibility between client, designer and contractor.

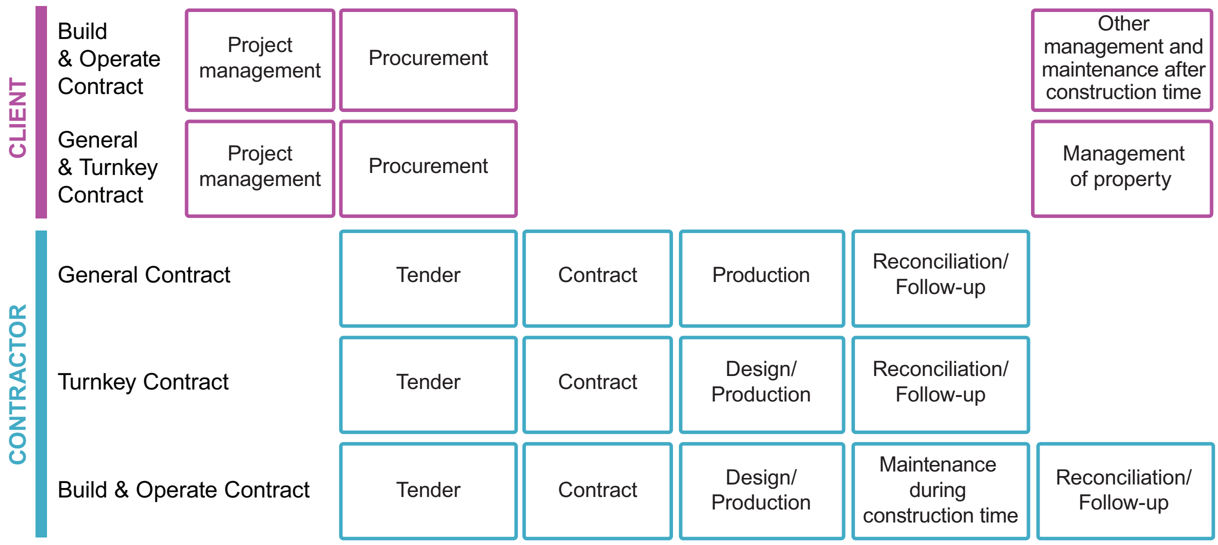


Figure 3.1 Contract forms according to Fant (2010) and Johansson Sundqvist (2005).

In public procurement the lowest price principle applies and the contracting process starts with a tender stage (Nordstrand, 2008). There are special forms of procurement (public procurement included) that leave openings for other criteria when the best offer is evaluated. These criteria may include skills and risk management, e.g. soft parameters. Prior to the tender stage, specifications are made available (Fant, 2010).

During the tender period, the business manager (agent) and estimating department along with expert support, make calculations for general and turnkey contracts. This process includes making a risk and opportunity analysis to elucidate precisely the risks and opportunities of the project (Ottosson, 2009). The focus is on the economics of the project, i.e. the uncertainty in the budgeted cost, although it is also possible to include any risks, such as potential problems with sub-contractors or potential communication problems between client and contractor (Fant, 2010). These risks can be viewed as unexpected events with an impaired economic consequence if they occur. According to Taroun (2013) there is a demand from the construction industry for greater accuracy when assessing the cost of unexpected events associated with construction work.

The difference between general and turnkey contracts is that the design process is included in turnkey contracts but not in general contracts. The difference between these two and build and operate contracts is that the maintenance required during the construction and maintenance period (which may be several years) is included in build and operate contracts. In build and operate contracts the design stage is included, which is also the case in a turnkey contract (Figure 3.1). The focus in the following sections is on descriptions in general and turnkey contracts.

3.2. Remediation prior to housing and property development

Purchased land that is due to be redeveloped into a residential area requires a new detailed plan showing the future land use and providing guidance, for example, on what the area should look like. The process behind a detailed development plan of this nature is controlled by the Swedish Planning and Building Act (2010:900).

Planning and Building Act

A detailed development planning process is handled by the municipality, which will decide if, when and how the detailed development plan will be prepared. The municipal authority is also responsible for the content, i.e. the future land use, e.g. residential or business, and other details, such as the number of floors in the buildings. The detailed development plan is legally binding. The building permit is decided based on the detailed development plan (Swedish, National Board of Housing. (2010)).

The detailed plan is sometimes developed in close association with a construction project. In such cases, the site developer can in practice initiate and prepare parts of the detailed plan proposal. However, the municipal authority still has the formal responsibility, i.e. it controls the planning process and makes the formal decisions (Swedish National Board of Housing, 2010).

A detailed development proposal usually includes a map, a description of the plan and a description of the implementation. In some cases it also includes an environmental impact assessment. The proposed detailed development plan is presented to provide an opportunity for stakeholders, e.g. the community, to express their opinions. The plan is adopted by the Building Committee and in the case of more extensive plans, by the City Council. The plan may be appealed to the County Administrative Board, whose decisions can be appealed to the government. If the plan does not carry leave to appeal, or if an appeal is rejected, the plan takes legal effect (Familjebostäder, 2013).

Planning and Building Act and the Environmental Code

It is the Environmental Code that governs the remediation work and the Planning and Building Act that governs the detailed development process. These two enactments are applicable when an area is redeveloped from, for example, an industrial site into a residential site. There is no link between these regulations, neither in the Environmental Code nor in the Planning and Building Act. This makes it difficult to develop the property, regardless of whether it is a private developer or the municipal authority that is responsible (Swedish National Board of Housing and SEPA, 2006).

The Swedish National Board of Housing and SEPA (2006) present two cases, one where remediation measures are implemented before the development plan is ready and the other case the opposite. They conclude that regardless of which case is applied, certain remediation measures can be carried out during the planning process, such as ground surveys and feasibility studies (Figure 3.3). The first case facilitates the planning process as the possibility of development specified in the detailed development plan is based on land suitability, which in practice is only known after remediation is carried out. On the other hand, to actually invest in remediation work before a formal decision has been made about future land use may pose a risk to the developer.

The situation where there is uncertainty regarding when to commence remediation implies that it is important for the developer to have a good understanding of the planning process and remediation process to avoid the risk of tying up money in a development project over a long period. Another risk associated with this issue, and which should be avoided, is initiating remediation too quickly when remediation targets have not been established according to the upcoming detailed development plan. This can result in remediated land that proves to be unsuitable for the buildings or the location of buildings specified in the detailed development plan when the plan is due to come into force (Risberg, 2012).

Risberg (2012) describes ambiguities between recommendations in the Planning and Building Act and the Environmental Code, both of which govern the remediation work, and between the Planning and Building Act and the Environmental Code when remediating for a change in land use. She suggests starting from the Planning and Building Act and working in parallel with the Environmental Code since the latter is stricter and is arranged in steps.

3.3. Remediation in civil engineering projects

A remediation project is a construction project *per se* but can also be a prerequisite for housing or other types of civil engineering projects. The reason for the remediation could have an impact on the execution, e.g. the remediation goals and the technique employed. Civil engineering projects differ with regard to the stage at which the contractor becomes involved, i.e. the design or contractor stage, see Figure 3.1. These circumstances affect the level of detail of the material provided by the client.

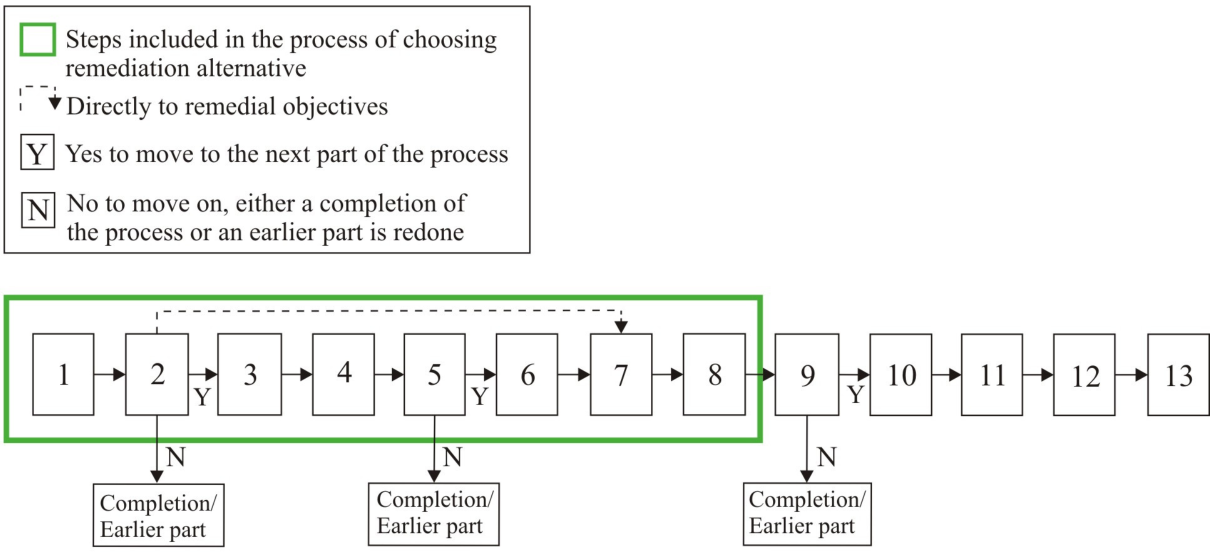
In a general contract, the documents from the client are well defined, with numerous lists of what needs to be performed to fulfil the contract, such as the amount of soil to be excavated (Nordstrand, 2008). In most cases, the baseline studies take the form of one or several consultant studies. As regards potential contamination, this is mentioned in the specifications and ideally previous reports should be enclosed with the tender. In the inventories, the amount of soil to be excavated, clean as well as contaminated is stipulated. All amounts of soil clean or contaminated, is regulated at the end of the reconciliation. Hence, if more contaminated soil than estimated is present, which in most cases means an increase in the excavation volume, the contractor gets paid for this at the end of the project. If unknown contaminants are discovered during the course of the work, this could result in extra costs due to a time delay because of investigation of the contaminant to determine the type and extent. In the normal case, it is the client that covers the cost of a previously unknown contaminant discovered during the course of the work (Fant, 2010).

A turnkey contract is a form of contract where the contractor is responsible for project design as well as the actual construction (Söderberg 2011). In turnkey contracts, the background documentation related to contamination is handled in the same way as in a general contract. A turnkey contract is used if the product ordered is very complex or if the purchaser does not have knowledge of how to perform the work (Fant, 2010).

Turnkey and partnering contracts leave more scope for the inventive contractor to come up with proposals for solutions and to try to find the best solutions, e.g. an innovative remediation. Turnkey contracts can also lower, for example, the project risk since the contractor has more control over the project. On the other hand, a general contract is strictly controlled, which could also be a way of controlling project risks.

Remediation process

Figure 3.2 shows a working methodology flowchart of the process of choosing, implementing and following up a remediation alternative. The description includes decision steps as well as working steps for Swedish projects. Feedback is possible between different steps, such as the feasibility study and the remediation alternative selection process back to the risk assessment (SEPA, 2009a). Guidelines are provided mainly to guide remediation of government-financed remediation processes. However, they can also be used when remediation is initiated as a result, for example, of redevelopment by a private project owner as the supervisory agency tends to follow these guidelines (SEPA, 2009a). For a more detailed description of the different steps, see Brinkhoff (2011).



1 Formulation of remediation goals
2 Survey and investigation decisions
3 Surveys and investigations
4 Risk assessment
5 Decision regarding the need for remediation
6 Feasibility study
7 Remediation alternative selection process
8 Proposal and quantifiable remediation objectives
9 Implementation decision
10 Preparation of remediation alternatives and specific remediation requirements
11 Implementation
12 Follow-up and documentation
13 Completion decision

Figure 3.2 The process of choosing, implementing and following up a remediation alternative.

Excavation can be a single remediation technique used at a contaminated site or a prerequisite for other remediation techniques. It can also be performed in combination with other techniques. Excavation used as a single technique with removal of soil and disposal through landfill as the end result are commonly used in Sweden. These excavations are called environmental excavations in contrast to the technical excavation performed before the construction of a building. Sometimes these two excavations interact when building on contaminated land. The main concern during excavation, apart from reducing the contaminated soil volume, is to secure the work environment since there may be a risk, for example, of collapsing excavation pits, emissions and dust (Helldén et al., 2006). For further and more detailed information on remediation in construction projects and different remediation techniques, see Brinkhoff (2011).

Liability and legal requirements in construction on contaminated sites

Requirements stipulated under the various provisions of the Swedish Environmental Code cover work on a contaminated site. This applies to development or any other course of action on the site. It is the responsibilities listed in the General rules in Chapter 2 of the Environmental Code that apply.

In addition to these rules, a remediation measure can in itself be considered environmentally hazardous and as a result additional requirements according to Chapter 9 can be imposed on the operator. Excavation work could pose a risk of contaminant spread, increased exposure or recontamination of the remediated soil. If such risks occur, which is normal, it is compulsory to notify the supervisory authority. The same applies if a contaminant is detected. Responsibility rests with the owner or user of the property. This obligation also applies in the case where new contamination is discovered at a known site (Swedish National Board of Housing and SEPA, 2005).

3.4. Project risks in construction work

Ottosson (2009) differentiates between the undesired events connected to the product and the project. The latter could affect the former but in an analysis it is important to be clear about which events are assessed and mitigated. In this thesis we are concerned with the events that affect and generate consequences for the project. These could, for example, be:

- Uncertainties in the baseline studies
- Badly or incorrectly defined assignments
- Insufficient time for completion
- Late decisions or permits
- Groundwork problems
- The sub-contractor's financial situation
- The client's financial situation
- The work environment

Unexpected events originate in all time periods of a project, from the very beginning to the very end. Continuous risk identification and evaluation, followed by mitigation, is therefore necessary for a successful project (Ottosson, 2009).

Project risks for developers of contaminated sites

Early estimations of the contamination situation provide information about unexpected events that could have negative implications for the entire project later in the process. As in any land development project, project risks exist although for any type of work on a contaminated site, risks linked to contamination and the way they are handled are extremely important. Knowledge about contamination, soil profile, groundwater, earlier activities and so on is necessary at the beginning of a building project in order to maximise the financial outcome at a former contaminated site (Rao, 1994; Tilford, 2000).

Companies building on potentially contaminated sites such as (1) former industrial sites, (2) disposal sites with excavated soil, or (3) sites with landfill material, are aware of the risks associated with those sites. A common project risk is the emergence of a more extensive contamination situation than could be foreseen, which is not unusual (Tilford et al., 2000). If this risk becomes a reality, the consequence could be a delay in the project or at worst it could bring the project to a halt as only a limited amount of money has been allocated for remediation. The estimate of how much it will cost to remediate a property gives the developer a remediation 'cost space', see Figure 3.3.

Another risk when building on former contaminated sites is the stigmatisation of a property, see Figure 3.3. In the worst case, stigmatisation could result in a situation where it is very difficult to sell the houses that are built. It is thus important to have a good and early understanding of the risks and opportunities in a project involving construction on a contaminated site.

The impact of detrimental conditions, such as contamination, on the value of a property has been investigated by Bell (1998). He developed several detrimental condition models for different situations. Figure 3.3 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 site in question, (B) shows how the property value is affected by the contamination, (C) is the assessment of the contamination and (D) is the remediation. Activities such as monitoring of the site after remediation has been completed is denoted by (E) and (F) is the possible remaining impact of any market resistance, i.e. stigma effects (Bell, 1998). The remediation 'cost space' could be interpreted as the difference between the cost of purchasing a contaminated site (B) minus the cost of assessing, remediating and monitoring the site (C-E).

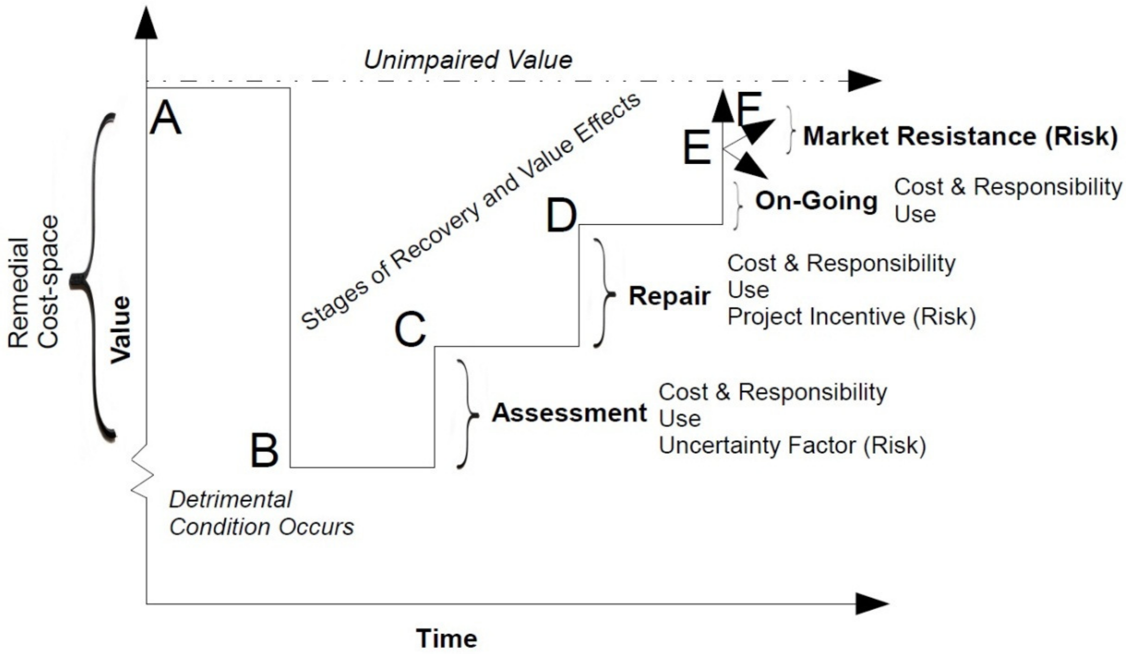


Figure 3.3 Detrimental Conditions Model by Bell (1998).

Project risks in the relationship between client and contractor in general and turnkey contracts

A general contract has a simpler responsibility relationship between the client and the contractor compared, for example, to turnkey contracts. The client has only one partner, the building contractor, which makes it less 'risky' for the client compared to shared contracts, where the client is responsible for all sub-contracts, construction being one of them. However, the contractor's responsibility in general contracts is subject to project risks related to cooperation with the sub-contractors, e.g. if a sub-contractor does not deliver what has been agreed. There is always a financial risk for the contractor that the bid amount is not sufficient to fulfil the contract. The reason for this is that the contractor most often needs to cut back on possible profit, e.g. by hiring a sub-contractor, since the contractor wants to present the lowest bid to the client to win the contract (Söderberg, 2011).

Turnkey contracts include design and construction work by the contractor. This approach is the subject of debate about the cost-effectiveness of this solution compared to a general contract, where the design is the client's responsibility and the design tender is also subject to the lowest price. From a responsibility point of view, this type of contract is much less complicated than other forms since it is an agreement between two parties that can be regulated by those parties (Söderberg, 2011).

Risk management in construction projects

Ottosson (2009) describes the risk management process for construction companies and presents an overview of the type of project risks and the management of those risks in the construction process. Risk management is a standardised and widely accepted procedure. A detailed description can be found in the international standard issued by the International Organization for Standardization (ISO, 2009).

Risk assessment in construction projects is often performed in a qualitative or semi-quantitative assessment manner. In large projects or during a tender process, quantitative methods can be used, such as the successive method, the expected value method or Monte Carlo simulations. A quantitative risk assessment provides decision support for risk management by integrating the probabilities and consequences of unexpected events with the possibility of including uncertainty in estimated probabilities and consequences (Ottosson, 2009).

According to McManus et al. (1996), the same risk elements exist in remediation work as in regular construction work. It is thus reasonable to assume that there is a need for greater accuracy when assessing the cost of unexpected events associated with remediation. Such an assessment would provide an estimate of the cost to be added to the budgeted cost, i.e. contingency costs, and provide the design and project team with improved decision support. An example of decision support could be determining which type of measure or combination of measures would be sufficient to reduce the risk of remediation costs spiralling out of control due to unexpected events.

4. SUSTAINABLE REMEDIATION

This chapter provides an introduction to the concept of sustainable development in general as well as different perspectives on sustainable remediation and appropriate frameworks. This chapter also includes a presentation of methods for assessing the sustainability of remediation and other civil engineering projects.

4.1. Concept of sustainable development

The idea of sustainable development began to take shape in the global arena at the 1972 UN Conference on Human Environment. Agreement was reached by the 113 countries at the conference to clean up the environment and to begin addressing 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 well received by the Third World, which saw the new agenda as yet another way of impeding Third World development (Newman and Kenworthy, 1999).

In 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* (Brundtland Report) published in 1987 (WCED, 1987). Since the report was published, the term *sustainable development* has been used colloquially (Newman and Kenworthy, 1999).

In the summary of the Brundtland Report, the Commission states that the growing environmental problems are linked to enormous poverty in the South and unsustainable consumption and production in the North. The following quote 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 for how to think conceptually about sustainable development (Kemp and Martens, 2007). There are more than one hundred definitions of sustainable development. The essence is the same for all of them: sustainable development involves satisfying the fundamental human needs of man in an equal way while trying not to violate nature on Earth (Kemp and Martens, 2007).

The sustainable development concept is an ethical approach that can be classified as duty-based and anthropocentric (Bardos, 2009). Figure 4.1 (Beatley, 1994) shows the ethical approaches, illustrated in a coordinate system, ranging from utilitarian to duty-based (y-axes) and anthropocentric to non-anthropocentric (x-axes).

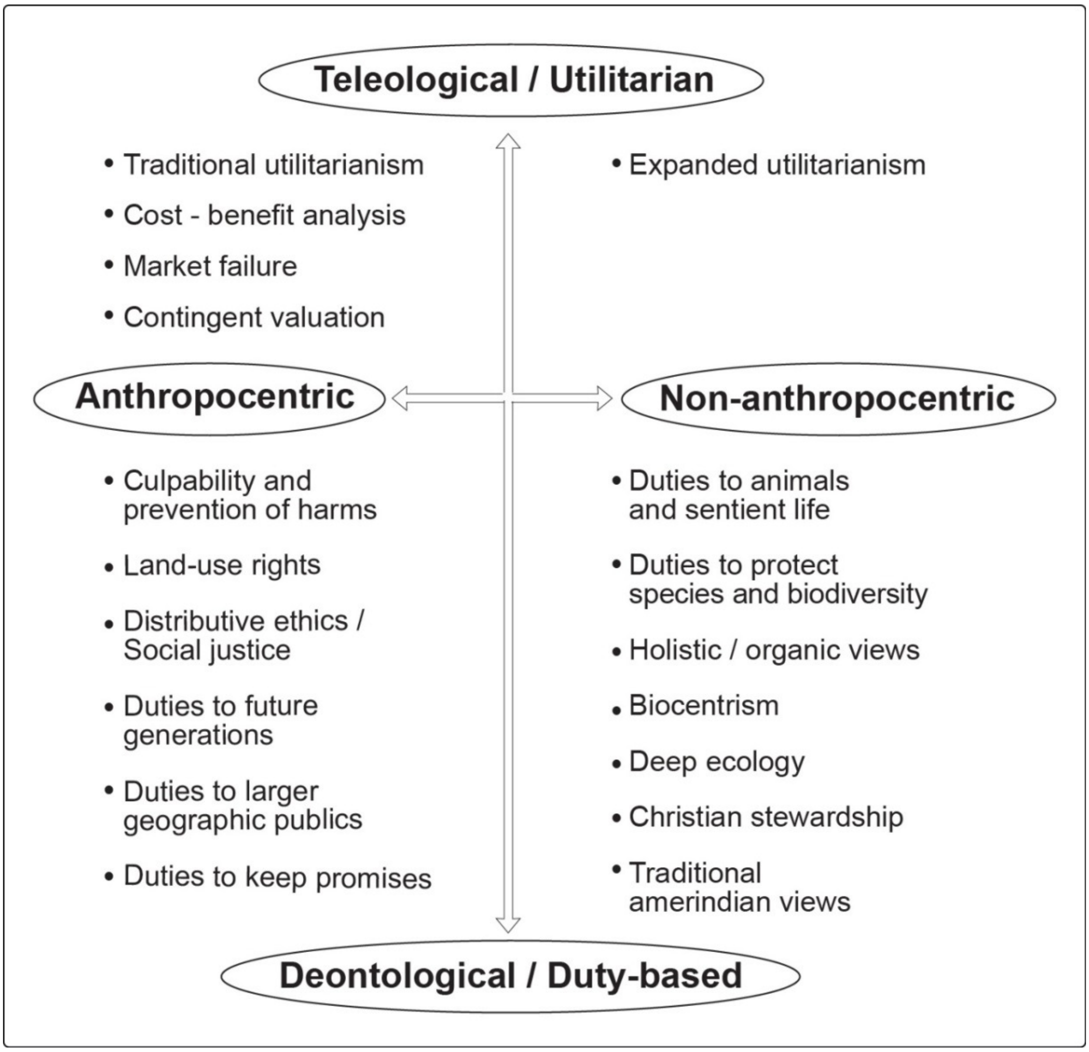


Figure 4.1 Classification of ethical approaches, from Beatley (1994).

Many attempts have been made to operationalise sustainable development. The most famous is the three-pillar concept, also called P3, which stands for Planet, People and Profit. P3 is either visualised by the pillar structure, overlapping circles or concentric circles (Adams, 2006). The last two are presented in Figure 4.2. The circles illustrate the environment, society and the economy. When these aspects interact, sustainable development can be achieved (Kemp and Martens, 2007).

The dominating model is a Venn diagram of overlapping circles. Overlapping circles imply the equal importance of all three sustainability domains. The 'bull's eye' model (Figure 4.2, right-hand side), indicates on the other hand that the environment is the fundamental and most important domain, since humans (or the social domain) cannot exist without a functioning ecological domain (see e.g. Scott Cato, 2009). The social domain embraces an economic domain, since the economic system cannot exist without humans. In this model, the economic system is regarded as being the least important domain.

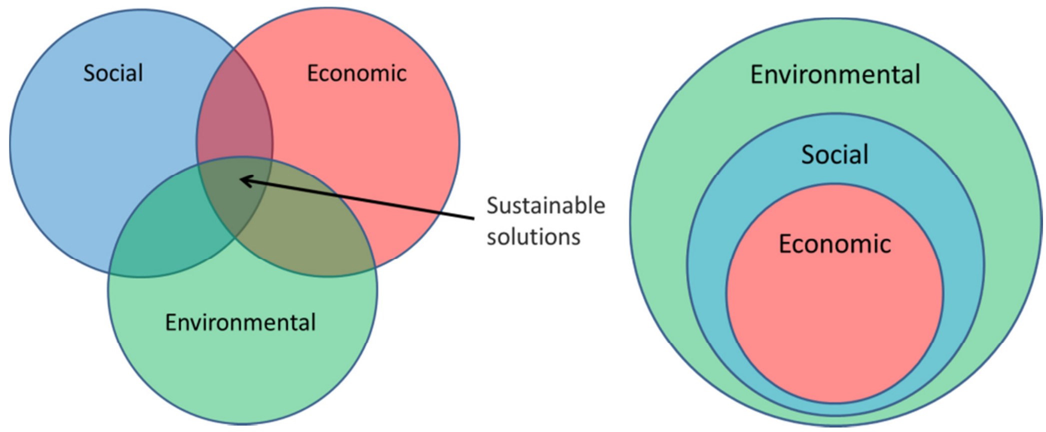


Figure 4.2 Two common sustainability models, 'Venn diagram' model (left) and 'Bull's eye' model (right) (Adams, 1996; Scott Cato 2009).

Sustainability science is an interdisciplinary field where economic, social and development studies are combined in order to acquire a better understanding of the complex dynamic interactions between the environment, society and the economy (Kasemir, 2003). Bleicher and Gross (2010) state that sustainable development must be seen as being dependent on space, time, scale and the players involved. Any understanding about sustainability or sustainable development must be context-sensitive.

4.2. Sustainable and green remediation

Sustainable remediation is a growing field of knowledge and according to Bardos et al. (2002) it supports the goal of sustainable development on a strategic level through:

- the act of conserving land as a resource
- prevention of the spread of pollutants into the air, soil and water
- reducing the pressure on greenfield development

The positive effects derive from minimisation of risks to humans and the environment, which is the fundamental driving force behind remediation measures. However, certain negative effects can arise while managing these risks (Vegter, et al. 2002, SEPA 2009a, Bardos, et al., 2011). These negative impacts could take the form of high energy consumption, production of by-products for disposal, use of non-renewable resources, emitting greenhouse gases (GHG) generation of dust and road accidents resulting from transport, i.e. risks related to transfer from one place to several other places. These negative impacts should not exceed the benefits of remediation (Bardos et al., 2002; Bardos et al., 2011). Hence, frameworks, methods and tools are needed to handle both the positive and negative effects of remediation measures.

Internationally, the USA has been working on issues related to sustainability frameworks, such as the first Sustainable Remediation Forum (SuRF) initiative and the Green Remediation initiative by the United States Environmental Protection Agency (USEPA). In Europe, SuRF-UK has published a framework document within Contaminated Land Applications in Real Environments SURF-UK (2010) SuRF-UK suggests a general framework for assessing the sustainability of soil and groundwater remediation that is broad enough to apply across different timescales, site sizes and project types (Bardos et al., 2011). Such a wide framework places sustainable remediation in the context of sustainable management of contaminated land.

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). In the US, the focus has been on trying to select the most eco-friendly technology, focusing mainly on energy use, to achieve a given remedial objective (SURF-UK, 2010). This strategy is known as green remediation. Sustainable remediation differs from green remediation in the fact that, according to the Sustainable Remediation Forum for the UK (SURF–UK, 2010), it considers remediation to be part of the broader sustainable development objectives of the project and not just selecting the most 'eco-friendly' technology.

Furthermore, the proposed European Soil Framework Directive (Critto et al., 2006) recognises that soil functions are critical for ecosystem survival and hence for the services that the ecosystem can provide for humans. The proposed Soil Framework Directive is likely to demand evaluation and management of soil functions and services in future remediation projects (Volchko, 2014).

4.3. Assessing sustainability

With the aim of achieving sustainable development, tools have been developed to assess whether or not a transition towards sustainability is taking place. Ness et al. (2007) presents a framework for sustainability assessment tools where available tools are categorised, see Figure 4.3.

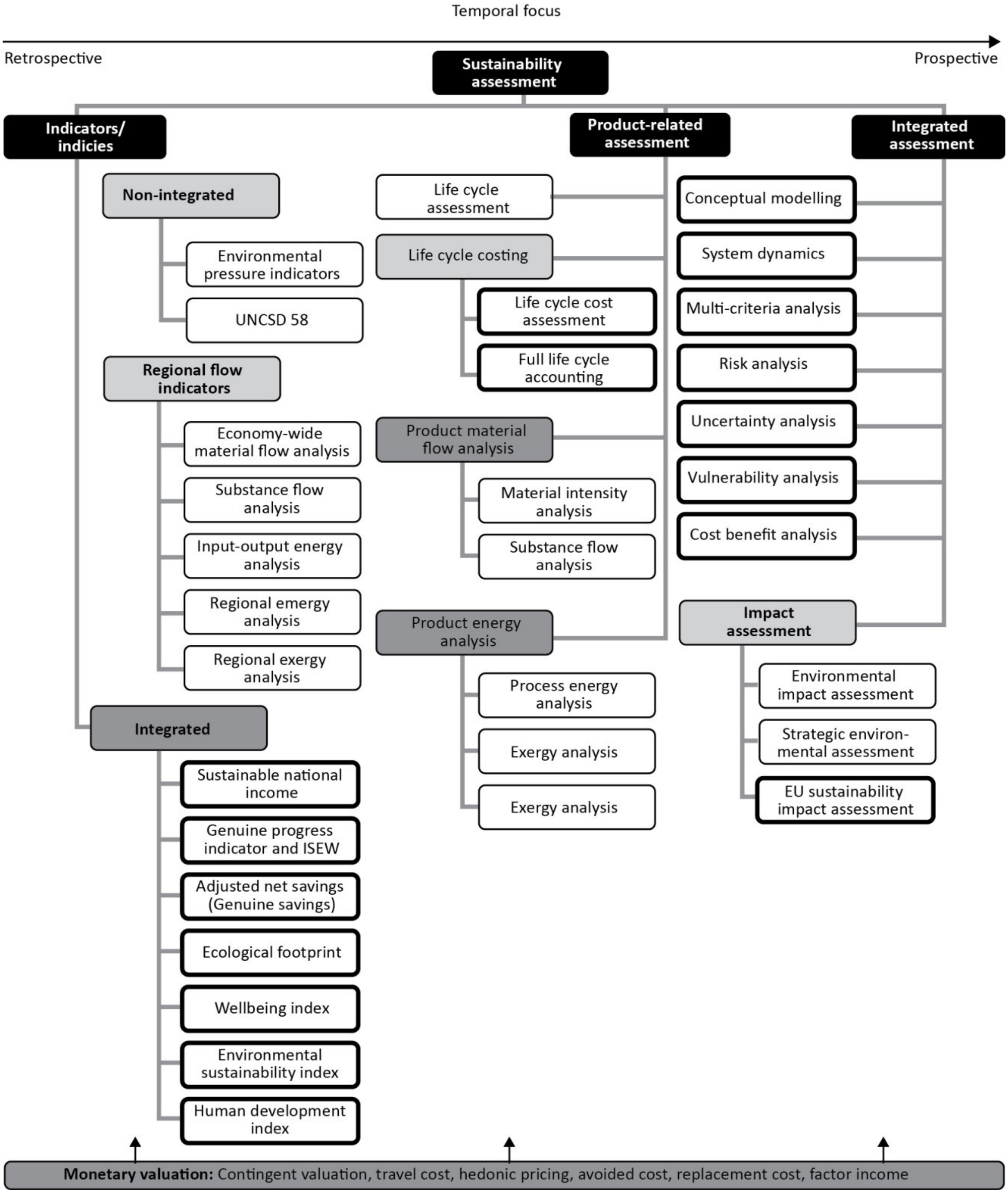


Figure 4.3 Framework for sustainability assessment tools, from Ness et al. (2007).

The framework has a temporal focus along with the object in focus for the tool. The monetary valuation, see bottom of Figure 4.3, can be used at any time. The boxes with bold frames are tools that enable an integrated assessment to be made of nature-society systems in a single evaluation, e.g. Life Cycle Cost Assessment (LCC) and Multi-Criteria Analysis (MCA) (Ness et al., 2007)

Another way of categorising tools and methods for sustainability assessment, in addition to what is shown in Figure 4.3, is to categorise them based on their aim. Therivel (2004) describes three main categories of sustainability tools: (1) tools that aim to describe and monitor the sustainability status, (2) tools that aim to modify people's perception and actions towards a sustainable way of life and, (3) tools that aim to predict and evaluate the effects on sustainability.

4.4. Methods for assessing sustainability in remediation projects and other construction projects

Remediation

In the case of assessment of sustainable development there are no united guidelines or common methodology for sustainable remediation assessments that are used by all member states in the EU or in other countries. According to Woodward et al. (2009), this is a possible barrier to implementing sustainable remediation. Another possible barrier is the difficulty of equating results in a consistent metric since many of the factors that influence the outcome require a qualitative assessment.

SuRF-UK recommends a tiered approach, a qualitative and quantitative assessment, in order to assess sustainable remediation and stresses that the specific tool used is not that important but that the process and thought behind the assessment is important. SuRF-UK lists a number of decision support techniques that are of 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 4.1 (SURF-UK, 2010).

Table 4.1 lists techniques, both quantitative and qualitative. An example of a technique that has flexible coverage in the different elements of sustainable development, i.e. the economic, environmental and social categories, is a scoring/ranking system – MCA for example. It is worth noting that SuRF-UK lists CEA, which is normally used as a quantitative technique, as a technique that can be used both quantitatively and qualitatively.

Table 4.1 Decision support techniques of relevance to sustainable remediation assessment, amended according to SURF-UK (2010).

Technique	**Environmental**	**Economic**	**Social**	**Type**	**CLM Application ?**
Scoring/ranking system (including multi-criteria analysis)	Narrow to Wide	Narrow to Wide	Narrow to Wide	Both	Yes
Best Available Technique (BAT)	Narrow to Wide	Narrow	-	Qualitative	Yes
Carbon footprint ("area")	Narrow	-	-	Quantitative	Yes
Carbon balance (flows)	Narrow	-	-	Quantitative	-
Cost-benefit analysis	Narrow to Wide	Narrow to Wide	Narrow to Wide	Quantitative	Yes
Cost-effectiveness analysis	Narrow to Wide	Narrow to Wide	Narrow to Wide	Both	Yes
Eco-efficiency	Narrow	-	-	Quantitative	-
Ecological footprint	Narrow	-	-	Quantitative	-
Energy/intensity efficiency	Narrow	-	-	Quantitative	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	-	-	Qualitative	Yes
Financial risk assessment	-	Narrow	-	Quantitative	Yes
Industrial ecology	Narrow to Wide	Narrow to Wide	-	Quantitative	-
Life Cycle Assessment (based)	Narrow to Wide	-	-	Quantitative	Yes
Quality of life assessment	Wide	Wide	Wide	Qualitative	-

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

MCA and MCDA

MCA is mentioned by Therivel (2004), Ness et al. (2007) and Surf-UK (2010) as a method capable of handling assessment of different elements, e.g. social, environmental and economic. Moreover, MCA makes the decision process transparent and structured, thus providing decision support when there is a large amount of complex information (Belton and Stewart, 2002). MCA can be used for different purposes: (1) to identify the most preferred alternative, (2) to rank alternatives against each other, (3) to shortlist a set of alternatives, (4) to group alternatives or (5) to distinguish the acceptable alternative from the unacceptable alternative (DCLG, 2009).

Decisions can be complicated to a varying degree and the analysis can thus also vary in depth. For less complicated decisions it is possible to perform an analysis without scores, weights and a combination of these, creating an overall value for each alternative (steps 5-6 and 8 in Table 3.2). This type of analysis is referred to as an MCA while the more complicated analysis is termed a Multi-Criteria Decision Analysis (MCDA). An MCDA involves all eight steps shown below in Table 4.2.

Table 4.2 Steps in the performance of an MCA and MCDA. To distinguish an MCA from an MCDA, the steps below that reside in an MCDA only are highlighted in bold.

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 in relation to the criteria. **If steps 5 and 6 are included, this performance should be measured quantitatively by means of 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 obtain an overall value**
7.	Examine the result.
8.	**Conduct an analysis of the sensitivity of the results to changes in scores or weights**
9.	**Conduct a sensitivity analysis**

Several advantages of MCA and MCDA over informal judgement have been identified by DCLG (2009):

- It is open and explicit.
- The choice of asset, objectives and criteria that any decision-making group may make is open to analysis and 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 and they do not necessarily need to be left in the hands of the decision-making body.

- It can provide an important means of communication within the decision-making body and sometimes later between that body and a wider community.

In an MCDA, different alternatives are evaluated in relation to predetermined criteria. These criteria are meant to collectively cover all aspects of the overall objective chosen (Brinkhoff, 2011). For the assessment of soil and groundwater, SURF-UK has developed a set of sustainability indicators. The sustainability indicator set has fifteen overarching categories, five in each sustainability domain (SuRF-UK, 2011). They cover all sustainability issues that might arise in different projects and at different decision-making levels, i.e. from large brownfield redevelopment projects to selection of a remediation technique at smaller sites (Bardos et al. (2011)). The indicator set has not been developed for any specific tool or method but to provide a basis in the process of agreeing on project-specific indicators for sustainability assessment, where the focus is on the process itself as a means of creating active stakeholder participation in projects.

CBA/CEA

CBA and CEA are also mentioned earlier as having the capacity to incorporate all domains of sustainability. CBA is based on a 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 lose out from the selection of a specific alternative that is valued in monetary terms. The preferred alternative or project is the one that has benefits that exceed the costs. There are many different valuation techniques in CBA. Two techniques that are widely used are hedonic price technique and stated preference method.

CEA is an assessment made exclusively of all the costs of each alternative associated with reaching a specific objective but not considering the benefits. It is the alternative that achieves the specific objective at the lowest cost that is the most cost-effective (DCLG, 2009).

Other assessment methods for remediation

There are decision support tools that can be used to evaluate the impact of a remediation action on the environment (primarily). Examples of such tools are the LCA-based tools SRT, Site Wise ™, SIMA-Pro and the Swedish LCA tool developed through collaboration between several parties in Sweden but handled by the Swedish Geotechnical Association (SGF). These tools mainly estimate emissions of greenhouse gases, which are then converted into CO_2 equivalents (Ferdos and Rosén, 2013; Brinkhoff, 2011; SimaPro, 2014). An example of a tool, based on the MCA methodology and with a focus on sustainability, is the Samla tool produced by the Swedish Geotechnical Institute (SGI). Samla takes into account sustainability e.g. environment, health, resources, economy and social aspects (SGI, 2014). The Golder Sustainability Evaluation Tool GoldSet© is another example of a sustainability assessment tool based on MCA. GoldSet© can be used in a variety of fields, such as remediation and mining. See also (Cornish, 2014; Brinkhoff, 2011; Witton, 2009).

Sustainability and environmental assessment methods for housing and civil engineering projects

In housing projects, sustainability (environmental) certification systems such as LEED and BREEAM are an integral part of the construction industry. A certificate from either of these systems is confirmation that the environment has been taken into account in the building project. These systems evaluate, as a percentage of a total score, the degree to which a project fulfils a set of sustainability criteria(Kubba, 2012).

BREEAM certification is used for one building whilst BREEAM Communities considers a whole area of buildings. For civil engineering projects, BREEAM is currently developing BREEAM Infrastructure. This system will probably have a great deal in common with the only sustainability certification system on the market for civil engineering projects – CEEQUAL (CEEQUAL, 2012).

Another system for sustainability assessment of civil engineering projects that the Swedish Transport Administration are interested in is SUNRA, Sustainability for national Road Administrations developed in The Sustainability – National Road Administrations (SUNRA) project. SUNRA is part of the ERAnet 'Energy – Sustainability and Energy Efficient Management of Roads' trans-national research programme (SUNRA, 2014). SUNRA is not a rating system as CEEQUAL and BREEAM Infrastructure but aims at producing a sustainable project by including sustainability from early on and throughout the lifetime of the project. It is a cooperation between the client and the contractor (STA, 2014).

CEEQUAL

How LEED is viewed in Therivel (2004) can also be applied to CEEQUAL, i.e. a tool based on an advanced checklist. Checklists are considered to be relatively simple to use because they contain few quantifications and do not require special expertise in the area to answer the questions.

CEEQUAL is a tool used to assess how well environmental and social aspects are handled in a construction project, i.e. a checklist to improve performance with regard to environmental and social aspects in both the planning and execution phase. CEEQUAL is the only tool on the market for sustainability assessment of civil engineering projects. The tool is based on a method that uses a scoring system combined with weighting in order to reach a final result, which is reported as a percentage for the whole project. This result leads to a grade and a certificate. Evidence is gathered from the beginning through to the end of the project, which is when the certificate is awarded (CEEQUAL, 2012; Ek and Brinkhoff, 2013).

5. THE SUSTAINABILITY ASSESSMENT: THE SCORE METHOD

This chapter describes the sustainability assessment method SCORE (Sustainable Choice Of REmediation). The chapter covers the SCORE framework, the conceptual model, key performance criteria, the assessment procedure and the sustainability index.

5.1 SCORE Framework

The Sustainable Choice Of REmediation (SCORE) method is based on the decision support method MCDA. MCDA has been suggested by a number of authors, e.g. Harbottle et al. (2008), Rosén et al. (2009), Linkov and Moberg (2011), and Brinkhoff (2011), for integrating economic, social and environmental sustainability into a comprehensive sustainability assessment of alternative remedial actions. The SCORE framework (Figure 5.1) and method were developed in line with the view of the decision-making process put forward by Aven (2003). SCORE provides decision support when choosing between a set of remediation alternatives.

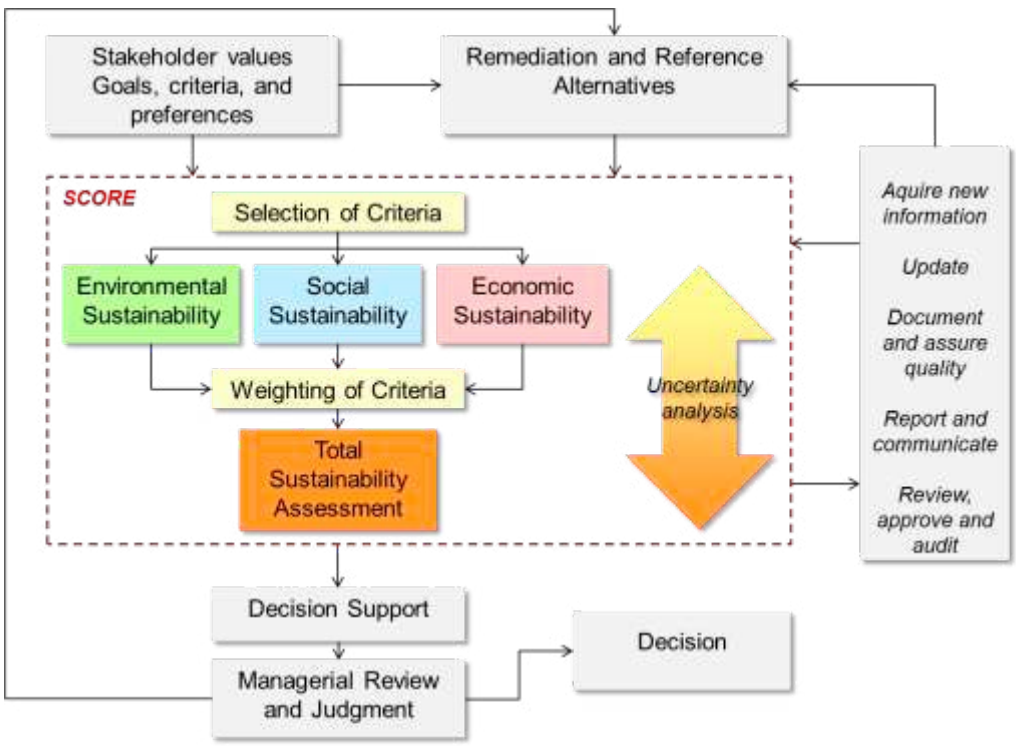


Figure 5.1 The SCORE decision support framework for sustainability assessment of remediation alternatives (Rosén et al., 2014).

Conceptual model and assessment boundaries

The conceptual model of SCORE is based on the cause-effect chain concept that is often used in risk assessment, see Figure 5.2. The *cause* of the effects is the remediation taking place at the particular site. The main *stressors* are (1) the change in *source contamination*, typically resulting in positive effects in terms of reduced risks to humans and ecosystems and new land use possibilities, and (2) 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.

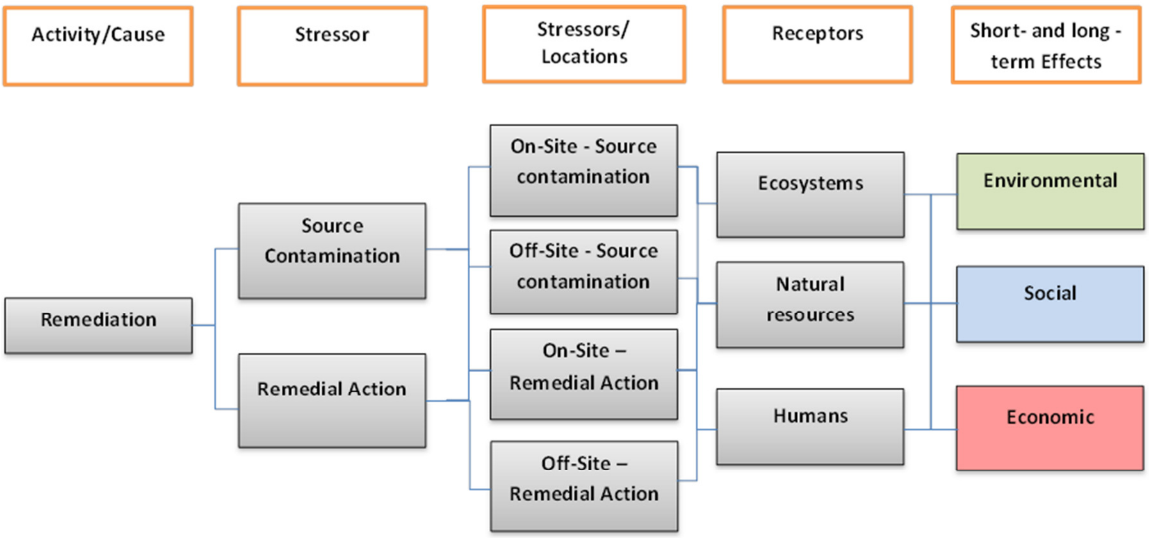


Figure 5.2 Conceptual Model of SCORE (Rosén et al., 2014).

Effects associated with a change in source contamination and remedial action can take place at different locations, both on-site and off-site. The on-site/off-site boundary needs to be defined in detail by the assessment team. On-site effects typically occur within the property boundary. Off-site effects can occur adjacent to the property (locally), or regionally or globally, see Figure 5.3. The receptors of the effects are humans, ecosystems and natural resources. The main types of long-term and short-term effects are environmental, economic and social effects.

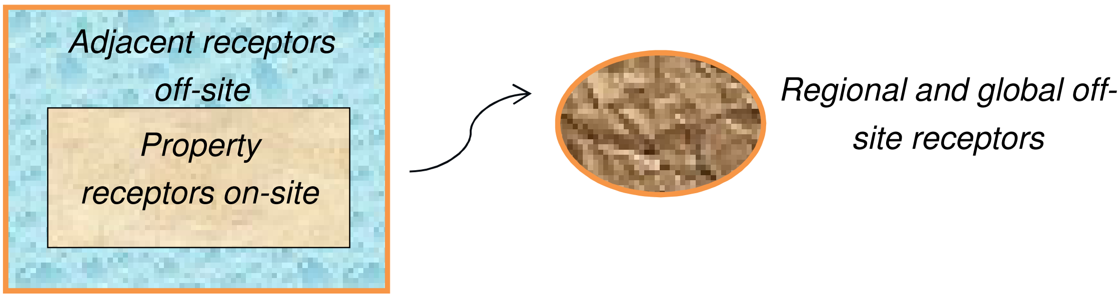


Figure 5.3 Schematic illustration of on-site and off-site effects.

SCORE has a system boundary that limits the assessment to situations involving transformation to a fixed future land-use scenario. The method has not been developed for the purpose of land-use planning, such as comparing the development of an industrial area into a residential area with the development of the same area into a recreational area. Such a comparison would require an extended social analysis different to the one that is currently included in SCORE.

Remedial alternatives evaluated by SCORE are specified prior to performing the MCDA and all effects (impacts) are assessed in relation to a *reference alternative*.

Moreover, double-counting is an issue that needs to be taken into account when performing a MCDA. Double-counting should not be confused with inevitable dependencies between effects among the domains in SCORE. An environmental change, for example, might have both economic and social effects. The domains can produce complementary information as they reflect ethical pluralism, i.e. an MCDA method such as SCORE can be a way of approaching incommensurability of values (Spash, 2013)).

5.2 Key performance criteria

The selection of the key performance criteria is based on an extensive literature review (Brinkhoff, 2011); interviews during expert group workshops that focus, for example, on sustainable remediation, flora and fauna and soil functions; focus group meetings in Sweden (Norrman and Söderqvist, 2013), and an earlier prototype of the method (Rosén et al., 2009). The identified key performance criteria are listed in Table 5.1.

Table 5.1 Key performance criteria for each sustainability domain in SCORE (Rosén et al., 2014).

Environmental domain	Social domain	Economic domain
E1. Soil E2. Flora and fauna E3. Groundwater E4. Surface water E5. Sediment E6. Air E7. Non-renewable natural resources E8. Non-recyclable waste	S1. Local environmental quality and amenity S1. Cultural heritage S2. Equity S3. Health and safety S4. Local participation S5. Local acceptance	Social profitability

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. The scorings are performed using available data, expert judgement, questionnaires and/or individual or group interviews.

The economic domain of the sustainability assessment in SCORE is performed by means of a CBA. The Net Present Value (NPV) is calculated for each remediation alternative by taking into account the costs and benefits for each remediation alternative and uses discounting over a certain time horizon to extract the net present value. The outcome is a measure of the social profitability. Cost and benefit items of the CBA (Table 5.2), are monetised in SCORE to the greatest extent possible, given the constraints of the assessment. As part of the uncertainty analysis in the CBA, SCORE allows for an investigation of who is paying and who is benefitting from the remediation. The analysis differentiates between the developer, employees and the public (Söderqvist et al., 2014).

The increase in property value (B1) and the remediation costs (C1) are the economic effects associated with the developer. Project risks (C1f) deal with the uncertainty of additional costs for the project, which is something that is very important for the developer of a contaminated site since such projects are typically associated with substantial uncertainties (Söderqvist et al., 2014). The developed PRA method presented in this thesis (Chapter 7) can be used for estimating C1f.

These uncertainties are described by Havranek (1999) and others and affect decisions about whether or not to implement a remediation measure and the type of technique to be used. The cost of remediating in a development project, e.g. building residential properties on a former contaminated site, must be weighed against the purchase price of the property and the future income it will generate. The space between these is called remediation cost space. Hence, there is a need for accurate information at an early stage about (1) costs (budgeted) and (2) costs of unexpected events, i.e. project risks that can develop into additional costs.

Table 5.2 Cost and benefit items used in the CBA in SCORE (Söderqvist et al., 2014).

Main items	**Sub-items**
B1. Increased property value on site	
B2. Improved health	B2a. Reduced acute health risks
	B2b. Reduced non-acute health risks
	B2c. Other types of improved health, e.g. reduced anxiety
B3. Increased provision of ecosystem services	B3a. Increased recreational opportunities on site
	B3b. Increased recreational opportunities in the surroundings
	B3c. Increased provision of other ecosystem services
B4. Other positive externalities than B2 and B3	
C1. Remediation costs	C1a. Design of remedial actions
	C1b. Project management
	C1c. Capital costs
	C1d. Remedial action
	C1e. Monitoring
	C1f. Project risks
C2. Impaired health due to remedial action	C2a. Increased health risks on site
	C2b. Increased health risks from transport activities
	C2c. Increased health risks at disposal sites
	C2d. Other types of impaired health, e.g. increased anxiety
C3. Decreased provision of ecosystem services due to remedial action	C3a. Decreased provision of ecosystem services on site
	C3b. Decreased provision of ecosystem services in the surroundings
	C3c. Decreased provision of ecosystem services at disposal sites
C4. Other negative externalities than C2 and C3	

5.3 Uncertainty

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. Furthermore, human subjectivity can result in different persons/groups assigning different scores to the criteria (Burgman, 2005).

The treatment of uncertainty in SCORE follows a Monte Carlo simulation approach, where statistical distributions represent the uncertainties in scores and cost-benefit items. Uncertainties are estimated by the assessment team based on professional judgement. Uncertainties in scores are represented by beta distributions and uncertainties in cost and benefit items are represented by log-normal distributions. For a more detailed description of uncertainty analysis in SCORE, see Rosén et al. (2014).

5.4 Sustainability assessment

The environmental effects are typically scored based on existing information, such as ecological risk assessments, samplings and laboratory analyses, soil function assessment (see Volchko, 2014), inventories of recipient conditions, and risk analyses of the remedial action, e.g. the risk of an overflow into a nearby stream from a dam used to collect contaminated groundwater.

As regards the social criteria, S1 to S5 (Table 5.1) are formulated in such a way that they can be scored by experts based on existing information, e.g. the human health risk assessment, environmental impact assessment, and on existing cultural heritage documentation but also, for example, on the distributional analysis within the CBA. Criterion S6 – local acceptance – is a criterion that should reflect how the local community perceives the different remedial strategies.

The expected effects of remediation on environmental and social sub-criteria are represented by scores from -10 to -6 for very negative effects and -5 to -1 for negative effects. If there are no effects at all, 0 is scored for that sub-criterion. The positive effects are scored in analogy with the negative effects.

In SCORE the economic domain is evaluated by calculating the net present value of costs and benefits for the alternatives under assessment. Given that all costs and benefits have been monetised and are thus included in the NPV computation, the remediation alternative associated with the highest NPV is the most profitable one for society (or, if NPV<0, the one that produces the least social loss).

Each key criterion and sub-criterion in the environmental and social domains is weighted in SCORE with regard to their relative importance. The weightings of sub-criteria and key criteria thus have a value [0,1] and the total weighting of all criteria (sub-criteria and key criteria, respectively) sum to 1.

Sustainability score

A sustainability score, i.e. a weighted score, is calculated for each remediation alternative for each domain (environmental, social, economic) as the weighted sum of the scores using a linear additive approach. In the economic domain, weighting of benefits and costs is done through monetisation in the NPV calculation.

To obtain a view of the resulting sustainability score of each remediation alternative, a normalised sustainability score is calculated. The normalised 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 normalised score can be used to rank the alternatives. The non-compensatory approach of SCORE facilitates an assessment of the degree of compensation between criteria and domains, thus providing information about strong sustainability (not allowing compensation) and weak sustainability (allowing compensation) of analysed remediation alternatives.

6. METHODS

This chapter describes the tasks performed and the methods used in this thesis to develop the PRA method.

6.1. Overview

Several tasks have been performed in this thesis and several methods have been used to develop a PRA method that can either form part of the SCORE tool or can be used as a standalone tool for project risk assessment in remediation projects (Brinkhoff et al., 2014, Anderson et al., 2014). The tasks and methods used are shown in Figure 6.1.

The first task was to describe the risk management framework based on standardised risk management (ISO, 2009) and to define what is meant by project risks, i.e. a monetary estimation of a risk of unexpected costs arising for the project owner. The second task was to identify project risk categories designed specifically for remediation project risk management. This was done by means of a) a focus group meeting and b) a complementary literature review. To quantify the risk costs, risk events were identified for each risk category.

The third task focused on examining the procedure for how to estimate monetary risks. This involved quantification of probabilities and costs by adopting the probabilistic view of, for example, Bedford and Cooke (2001). In task four – operationalisation of the suggested PRA method – a PRA tool was developed. The PRA tool addresses the uncertainty assessment in the PRA method and all the calculations. In task five, the PRA method was tested in a case study to refine the PRA method for practical use.

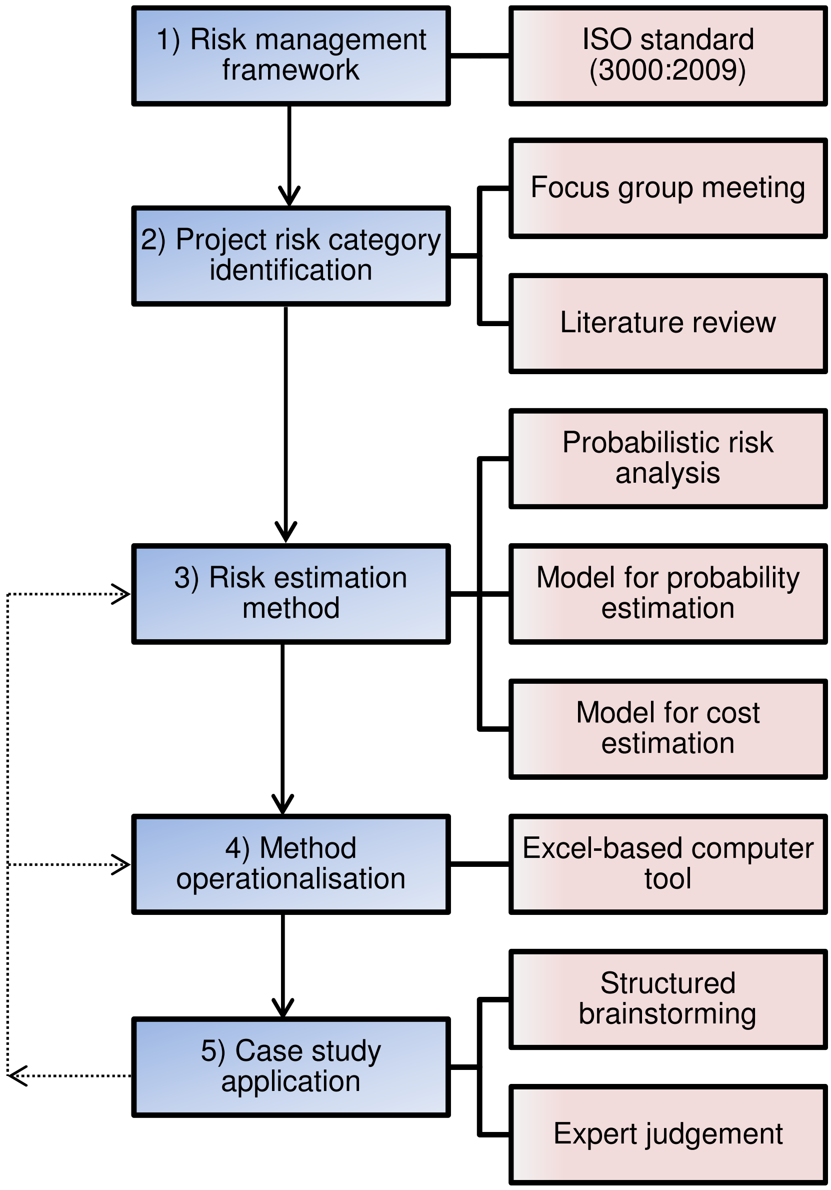


Figure 6.1 *Tasks, highlighted in blue, and methods, highlighted in red, are used to develop the PRA method. The iterative loop is shown by the dotted lines.*

6.2. Risk management framework

Figure 6.2 shows the different steps in the risk management approach as described in ISO 3000:2009, where the PRA method belongs to the risk assessment part (shown by means of bold lines and boxes in Figure 6.2). As described in ISO, the risk assessment includes (1) identification, (2) analysis and (3) evaluation of project risks. These three phases form the basis for the developed PRA method.

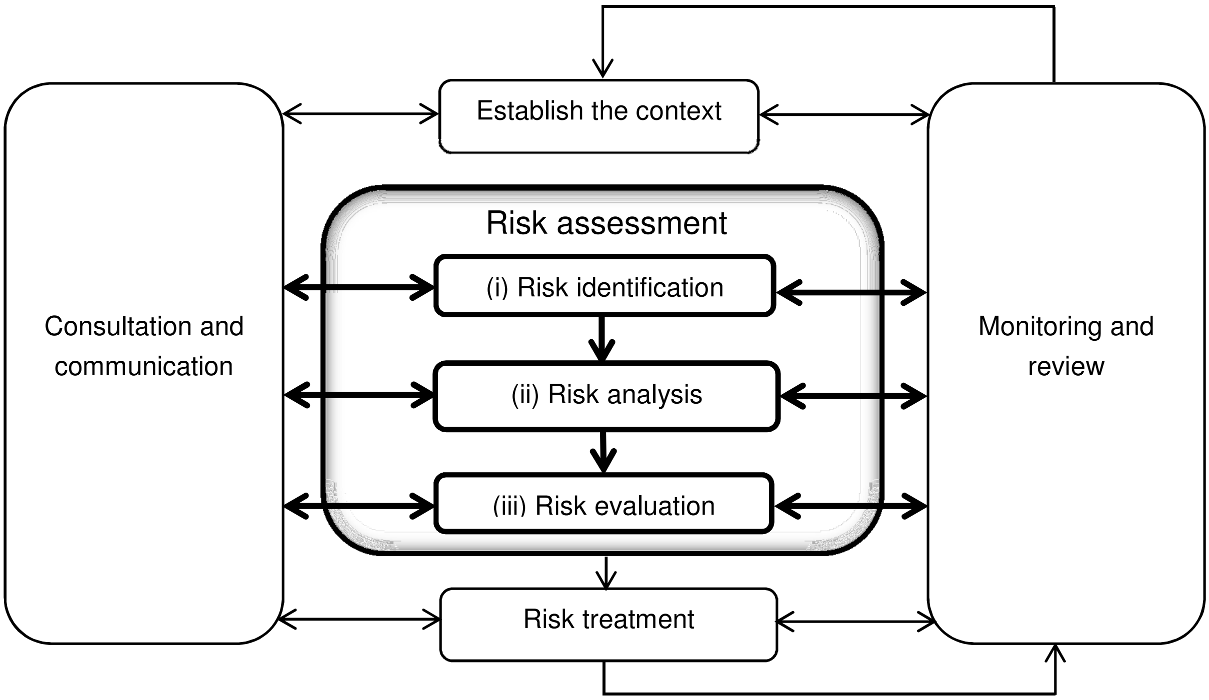


Figure 6.2 The risk management process (ISO, 2009). The risk assessment process is outlined in bold.

A detailed description of the risk management process can be found in the international standard issued by the International Organization for Standardization (ISO, 2009). Similar frameworks have been presented by IEC (1995), AZ/NZS (2004 a, b) and the Swedish Civil Contingencies Agency (2003).

6.3. Project risk category identification

Project risk identification can be achieved through checklists and brainstorming or other methods, e.g. the Delphi Method, Hazard and Operational Analysis (HAZOP) or Failure Modes and Effects Analysis (FEMA), combined with brainstorming sessions (described further in Bedford & Cooke, 2001; Aven, 2003; Burgman, 2005). The identification process should be performed case by case by the project organisation since many project risks are typically unique for specific projects.

In this work the identification of general project risk categories was carried out by using experts at a focus group meeting and a complementary literature review. Identified project risk categories should function as a checklist and point of departure in the application of the PRA method and should: 1) be viable in remediation projects prior to construction, 2) be general in scope, and 3) include all relevant project risks to support the project risk assessor.

Focus group meeting

Project risk categories were identified in a group discussion involving members of the remediation sector using the focus group technique. The purpose of focus group meetings is typically to learn about people's attitudes and opinions on a specific topic. It is a qualitative method and has been applied in disciplines such as social sciences, public health, anthropology, pedagogy, social medicine research, urban planning and marketing (Wibeck, 2010).

The participants represented construction companies, consulting companies, local (real estate office) and regional (regulatory agency) authorities and a government research institute. The semi-structured focus group meeting identified important project risk categories for construction companies in three phases: (1) before land acquisition, (2) during selection of a remediation method, (3) during implementation of the selected remediation alternative. After the meeting a summary of the discussion was circulated for review by the participants as well as those who were invited but were unable to attend. No additional comments were received on the summary circulated for review. A more detailed description of the focus group meeting can be found in Brinkhoff et al. (2014).

Literature review

To complement the focus group discussion, a literature search was conducted dealing with project risks related to remediation projects. It was difficult to find literature that had a well-developed checklist of risk categories. The literature review therefore focused on two sources: the Interstate Technology & Regulatory Council (ITRC) (2011) and Rosén and Wikström (2005). Unlike the focus group discussion, ITRC (2011) and Rosén and Wikström (2005) concentrated on project risks in publicly funded projects, i.e. their project risk categories cover a wider range of areas, including environmental, social and economic aspects. The focus group discussion concentrated on project risks for the land owner. For further details of the literature review, see Brinkhoff et al. (2014).

6.4. Method for risk estimation

Risks such as project risks are commonly defined as the product of the probability (*P*) and the negative or positive consequences (*C*) of an unexpected event occurring. The definition of project risks used in this thesis builds on this with specification regarding whose´ risks that are taken into account.

The definition is:

"*A project risk is the product of the probability that an unexpected event will occur while carrying out a specific remediation alternative and the economic consequence of that event for the construction project owner. The probabilistic risk cost is thus a possible but unexpected additional cost and not a result of the uncertainties of expected costs, i.e. budgeted costs.*" *(*Brinkhoff et al., 2014).

In this thesis probabilistic risk analysis includes uncertainty of *P* and *C*, is in line with approaches laid forward by e.g. Bedford and Cooke (2001). By representing variables *P* and *C* using density functions, the uncertainty of the outcome (in this case the economic risk) can be estimated and shown. Here *P* is represented by a beta model and C is represented by a lognormal model. By carrying out a Monte Carlo simulation, an expected risk cost (*R*) for each risk event based on the density functions for *P* and *C* can be generated, see Figure 6.3.

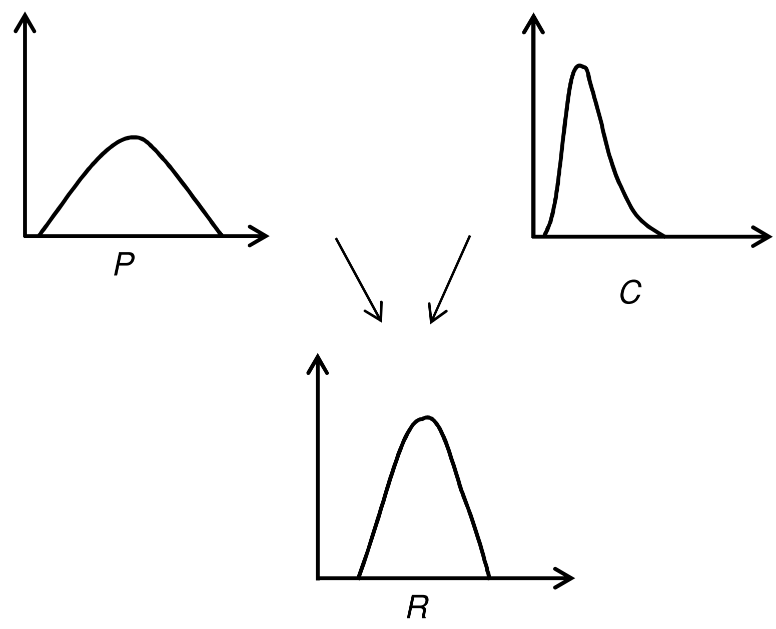


Figure 6.3 Illustration of how Monte Carlo simulation is used to include uncertainty in the input variables (P and C) for calculating the uncertainty of the resulting project risk (R).

6.5. Operationalisation

For a potential user of the PRA method, the vast amount of information generated in the PRA needs to be handled using some form of tool. Such a tool was developed in Excel format, denoted the PRA tool, and it can take into account the experts' uncertainty and enable an uncertainty analysis to be made of the result.

The probability (*P*) of an event occurring and its consequence (*C*) are quantified by assessing ranges between a lowest reasonable value and a highest reasonable value, represented by 5^{th} and 95^{th} percentiles of probability and economic consequences. The interval takes into account how certain the assessor is and it is a fairly easy way to express the two parameters that are needed for the chosen density functions of *P* and *C*.

The present value of the project risk (risk cost) is calculated by means of simulation, with the Excel add-in program Crystal Ball, in the PRA tool. Monte Carlo simulation randomly selects values from *P* and *C* a large number of times to generate a resulting histogram of *R*, see Figure 6.3. The outcome is a probability distribution of the economic value of a project risk for specific events, the project risk categories, and the total project risk cost for each alternative with associated uncertainties.

6.6. Case study

In the case study application, experts were used during structured brainstorming sessions. Brainstorming sessions with experts were used to identify risk sub-categories, risk events and risk sub-events, ascertaining the consequences for each risk or risk sub-event, (in words) in the case study application. Structured brainstorming encourages participation and contribution by all participants, in this case to identify risks (Burgman, 2005).

Experts were also used to estimate the probability interval of the event actually happening and (b) the monetary consequence if it did happen, also given as an interval. It is common to use experts during brainstorming sessions to estimate, for example, probabilities and consequences in risk analysis (Bedford & Cooke, 2001) since 'real data' can be difficult or impossible to find due to the uniqueness of the project.

The case study presents the opportunity to refine the developed method by using the iterative loop between the case study and the operationalisation of the method and also in some way the project risk method.

7. RESULTS

This chapter presents result of the tasks performed to develop the PRA method by giving the project risk categories and describing the project risk assessment (PRA) method and tool for remediation projects prior to construction.

7.1. Project risk categories

The project risk categories used in the PRA method are presented in Table 7.1.

Table 7.1 The seven suggested project risk categories.

Categories	**Explanations**
Remedial action	The *remedial action* category aims to capture risks associated with a specific remediation method. Examples of risk events within this category include the technical failure of the remedial action, such as breakdown of machinery, pumps and the soil material not working together with the machinery, e.g. sieving equipment, or the equipment not working at all.
Authorities/ authorisation	The most important project risks related to *authorities* include communication between the contractor, the environmental specialist and the authority, which in most cases is the regulatory agency for the project.
Concern and expectations	The *concern and expectations* category covers project risks associated with the concern experienced by the general public with regard to the remediation project. Examples of concerns that could generate project risks are a large number of transport movements and dust and noise issues. This risk is typically present in the project from the beginning until the end and may play a central role.
Project organisation and financial structure	Risks in the *Project organisation and financial structure* category are the procurement process and distribution and logistics contracts. Logistics covers both off-site transport movements and on-site logistics. Another major project risk during all phases of a project is the way in which the public sector economy as a whole is developing. A recession might mean that it is not financially viable to build houses on the property and hence not remediate.
Technical basis for judgement and technical competence	Project risks in the *technical basis for judgement and technical competence* category are linked to various uncertainties regarding the contamination situation at the site in relation, for example, to contaminant type, extent and amount. The risk of erroneous design and selection of a remedial action that is not cost-effective and time-optimal is also included in this category. A poorly performed initial study, e.g. a desktop and/or initial environmental soil survey, could be the root cause of the uncertainties. A suboptimal choice of remedial measure could also be a result of a lack of technical competence on the part of the consultants. The risk of unexpected leakage and spreading is also included in this category.
Liabilities	Risks related to *liability* matters are mostly present before the acquisition of a property. This could be relevant if a new contaminated area is detected on or close to the site during remediation. There is also a risk if the remediation goal is not achieved using the chosen remedial measure.
Other issues	*Other issues* could include events linked to the weather situation, break-in and/or sabotage. It is possible to gather issues within this category that are not covered by other categories.

7.2. PRA method

In this thesis the additional costs/contingency are included in a project risk and are termed the *risk cost*, i.e. the expected monetary cost for the remediation project or project owner (e.g. a construction company) due to an unexpected event. Figure 7.1 shows the PRA method (stepwise) from identification of risk sub-categories to a risk cost with impaired uncertainty for one or several remediation alternatives.

The PRA method follows the risk assessment procedure as presented in, for example, International Standard ISO 3000:2009, where project risks are identified, analysed and evaluated. Furthermore, the method uses probabilistic economic quantification of project risks, i.e. the project risk is a combination of the probability and the consequences of an unexpected event occurring prior to or during remediation. The PRA method also takes uncertainties in probabilities and consequences into account.

Risk estimation method - Probabilistic risk analysis

A project risk (R) is here defined as the product of the probability (P) and the negative or positive consequences (C) of an unexpected event (i) occurring during remediation. Eq. 1 denotes the risk calculation:

$$R_i = P_i \, C_i \qquad \text{(Eq. 1)}$$

A reduced budget is a positive consequence of an event and is accounted for as a negative cost, i.e. a benefit, in the PRA. Moreover, the P and C of each project risk are assigned probability density functions. The beta distribution is recommended for P and the log-normal distribution for C. After this, the mean risk cost for each project risk and project risk category is calculated.

This procedure generates a resulting histogram of R. The outcome is a probability distribution of the economic value of a project risk for specific events, the project risk categories and the total project risk cost for each alternative (Eq. 2) with impaired uncertainty.

$$R_a = \sum_{i}^{N} \sum_{k}^{K} P_{i,k,a} C_{i,k,a} \qquad \text{(Eq. 2)}$$

R_a = Total project risk for alternative a (a = 1,.., A) for events i (1,…,N) and category k (1,…,K)
P = Probability
C = Economic consequence

7.3. Stepwise working procedure of the PRA method

Risk identification

In steps 1 and 2 of the PRA method, see Figure 7.1, it is suggested that structured brainstorming sessions with experts are used to identify risk sub-categories and risk events associated with project risks by using the project risk categories (Table 7.1) as a starting point. Risk sub-categories and risk events are preferably identified for one remediation alternative at a time to make the identification process easier.

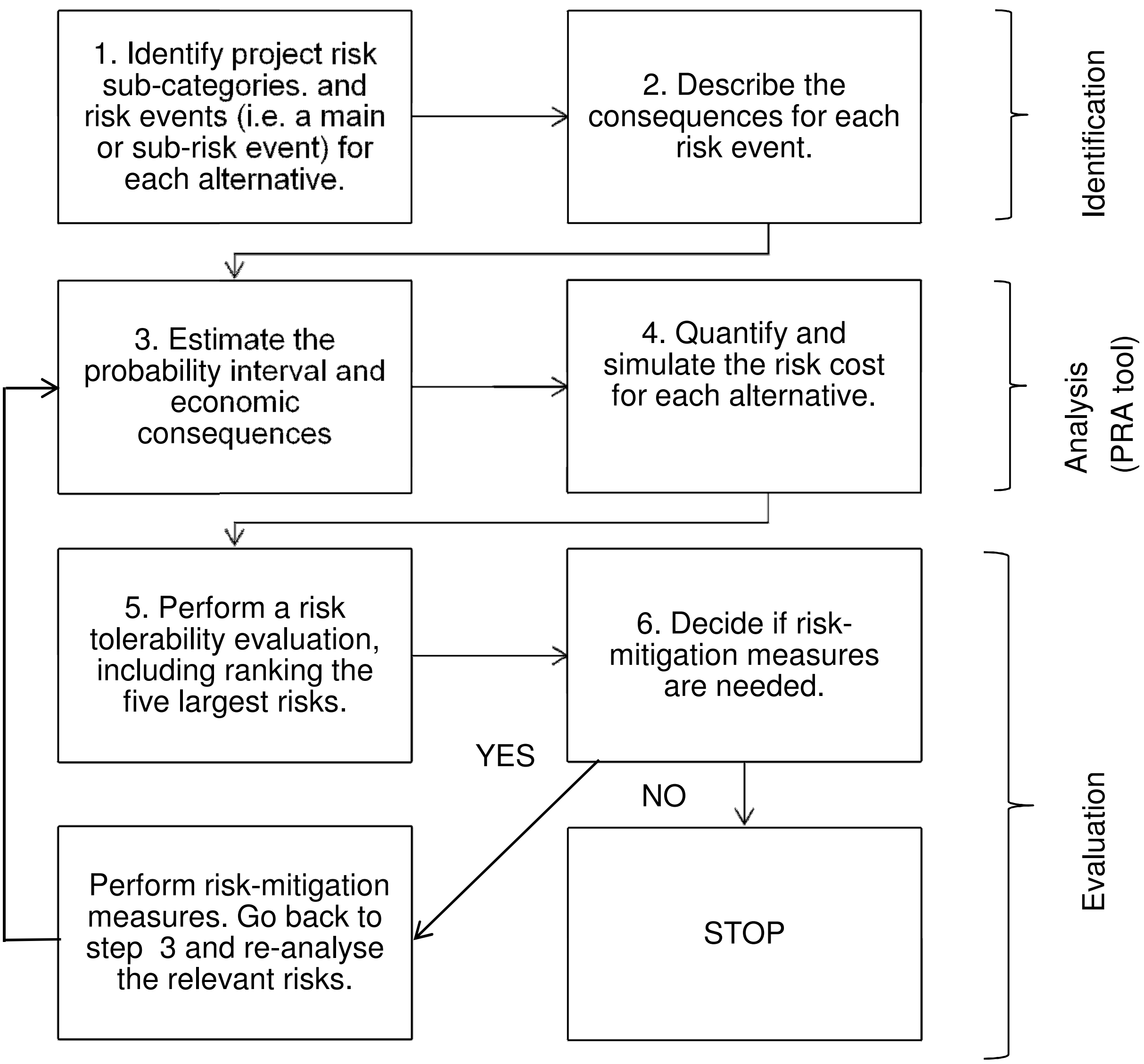


Figure 7.1 The suggested PRA method, described as a stepwise method with an iterative loop.

When the risk sub-categories are identified, the consequences associated with each identified risk event are first described in qualitative terms. In the following step, probabilities and consequences are quantified. The consequences are estimated in monetary terms, e.g. costs for additional working days or additional consulting time. Both probabilities and consequences are estimated with an interval to capture the experts' degree of uncertainty with regard to the estimation.

Risk analysis - PRA tool

The risk assessment according to the developed PRA method includes large amounts of input data that require computer assistance and to meet this requirement a computer-based tool based on the method was developed. In Figure 7.1 it is shown in what steps (steps 3 and 4) the computer tool is used. The PRA tool is based on Excel and is used as part of the SCORE tool (Anderson et al., 2014) as well as a standalone tool. In this study, Crystal Ball, which is an add-in to Excel, has been used for the Monte Carlo simulations, performed in steps 3 and 4 of the PRA method.

Estimation of the probability of risk events and uncertainties of economic consequences is conducted in steps 3 and 4 of the PRA and should be carried out by experts with experience of remediation projects similar to the project under consideration. The *P* and *C* of events occurring are expressed with an interval to manage the experts' uncertainty in their estimation.

The range of the uncertainty interval is represented by, for example, the 5^{th} and 95^{th} percentiles, which imply that 90% of all possible probabilities and economic consequences fall within this range. As part of the PRA tool, a Monte Carlo simulation randomly selects values from the probability density functions for *P* and *C* a large number of times – 10,000 times for example.

Risk evaluation

The results from the Monte Carlo simulation are evaluated in steps 5 and 6. It is possible to extract statistical parameters from the Monte Carlo simulation other than the mean, such as mode and percentiles, and it allows each alternative to be analysed with regard to: (1) the probability of having the lowest risk cost; (2) the uncertainty of the total project risk cost; (3) the contribution of each input variable to the total uncertainty of the project risk cost.

These analyses form the basis for the decision about whether certain project risks are unacceptable and should be mitigated. The PRA tool automatically lists the five largest risk costs and together with the sensitivity analysis it is assumed to provide a clear enough overview of where measures should be prioritised. If any unacceptable project risks are identified, measures should be taken (and accounted for in cost calculations, e.g. for remedial action) and the procedure then starts again in Step 3 by estimating new probabilities and/or consequences as part of the iterative loop.

8. CASE STUDY HEXION

This chapter presents the case study area and the investigations and measures that were suggested and performed on site. Details of the results from the PRA assessment in the case study, along with the results from the sustainability assessment using SCORE, are also presented in this chapter.

8.1. Introduction to Hexion

For about 180 years, the Hexion property (Figure 8.1) was the site of various chemical companies. Up until the First World War, linseed oil was produced and after that various chemical products were manufactured.

In recent years the plant has been run by the company Hexion Specialty Chemicals Sweden AB. Hexion Specialty Chemicals Sweden AB mainly manufactured binders for the coatings industry until it was closed down in April 2007. NCC AB then acquired the property, which it intends to redevelop into a residential area.

The Hexion property covers about 35,000 m^2 and is located approximately one kilometre east of the centre of Mölndal, just south of the City of Gothenburg in south-west Sweden. The area is the old centre of Mölndal. A lot of industrial development has taken place in this area because of the proximity to the river, Mölndalsån, with its falls, which were used to generate water power. The property has a distinct topography with a large variation in elevation (between 32 and 59 m asl) and it slopes in a south-westerly direction from the highest point in the east to the lowest point in the south-west.

The geology at the site is complex as the Gothenburg terminal moraine runs through the property. Terminal moraines mainly comprise till and fluvial material with some elements of clay. The entire southern boundary of the property slopes in a south-southeast direction towards the river, which runs just outside the south-eastern boundary of the property. Mölndalsån originates in Lake Stensjön and discharges into the Göta Älv River.

As a result of major topographical differences within the area, the depth of the groundwater table varies substantially, generally 2-10 m below the land surface. There is an artesian well located on the site. Bedrock outcrops in a few places on the property and also to the west and north-east of the property. Soil depth to rock varies from a few metres to about 20 metres. The area has been partially filled with various kinds of material, the thickness varying from 0 to 5 m, sometimes even deeper.

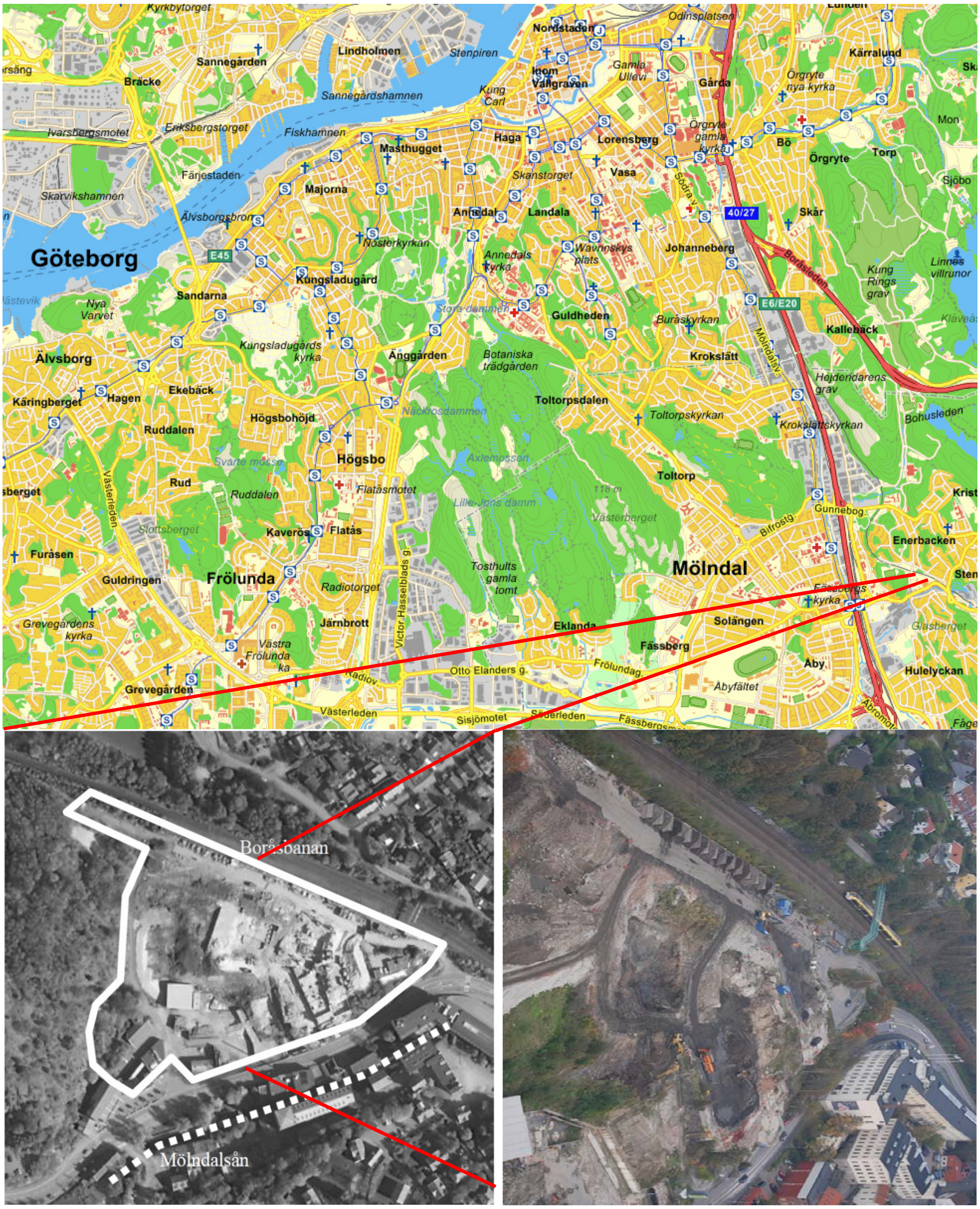


Figure 8.1 *A map of Gothenburg and Mölndal and two aerial photos of the Hexion site. The white line in the left-hand photo marks the border of the site and the dotted line marks the river, Mölndalsån (from Landström and Östlund, 2011). Photos: Eniro and National Land Survey of Sweden, Gävle, Sweden.*

8.2. Contamination and remediation objectives

As the chemical companies that existed on the site handled many different kinds of chemicals, contamination and remediation were expected to be a necessary part of land development. The first environmental field sampling was carried out in 1997 by KM Miljöteknik AB and since then several studies have been conducted. NCC conducted its first environmental field sampling when it acquired the property in 2007. The studies showed that large areas were unaffected or were only affected to a minor extent by past activities. Contaminants were mainly found near the land surface (0-1 m) but also at greater depths (4-8 m) in limited areas (Magnusson and Norin, 2007). NCC gradually expanded the sampling as the buildings on the site were demolished and access in certain areas increased. In total, approximately 900 soil samples were taken at 500 sampling points along with a large number of groundwater samples.

Sub-areas were identified due to the wide range of activities that were carried on in the past, including disposal, loading and unloading of material and storage of chemicals. The contaminants in the sub-areas consisted mainly of phthalates, lead and solvents in the soil and groundwater. A groundwater monitoring programme was established during the last few years the plant was in operation. According to the results, there was a slight leakage of contaminants from under the buildings. The concentration of contaminants was above the guideline values even though the concentration of contaminants in the groundwater as a whole was mostly below the detection limit. In all, some 25 groundwater sampling wells were installed by NCC on the property. The purpose was to investigate the presence of contaminated groundwater within the area but also to examine the potential for contaminant migration from the property. The results show that the groundwater was polluted in the source areas although no transport from the site could be detected.

A site-specific health and environmental risk assessment (Sweco, 2009) showed that the risks needed to be reduced, particularly to human health and possibly to ecosystems. This applied mainly to the top soil and the deep soil in smaller areas.

Quantitative remedial objectives were formulated for the substances/compounds that were most prevalent in the area at levels higher than the Environmental Protection Agency's general guidelines for sensitive land use (SWECO, 2009). The substances and compounds found were lead, barium, PAHs, aliphatic and aromatic hydrocarbons, ethylbenzene, xylene and the phthalate DEHP. Different quantitative remedial objectives were applied to surface soil and more deeply located soil.

8.3. Remediation

The remediation at Hexion was based on a 3D map of the area. The area was divided into squares, 10 by 10 m. Each square was assigned a contamination class based on extensive environmental investigations. In April 2011, phase 1 of remediation of the property commenced. In phase 1 the source areas previously identified through the environmental investigations were removed by excavation. Each square was excavated and any suitable soil was sieved. Secondary analyses were then made to verify the contamination class.

In some areas, however, extensive excavation was carried out to meet remediation targets due to newly identified contaminants. Around 58,000 tonnes of soil were excavated during phase 1 and around 32,000 tonnes were transported to disposal sites. The sieving procedure meant that about 40% of the excavated and checked soil could be reused within the project.

An important part of the project was to maintain good communication with the authorities and the neighbours to avoid misunderstandings and to reduce potential delays in the project. Before and during remediation, extensive contact was established between NCC and the supervisory authorities. Regular meetings were held and documented. Site neighbours were informed of the remediation plans before the project commenced and this was followed up during the course of the project.

The research projects (Chapter 2) that used the Hexion site as a case study area were carried out during the same time period as the Hexion remediation project. The research projects received continuous input from the Hexion project, enabling the sustainability assessment to be developed and refined. Several other case study sites have been used by the research projects. For information about these see (Volchko et al., 2014).

8.4. Remediation alternatives for project risk and sustainability assessment

The project risk and sustainability assessment was performed for four remediation alternatives (Table 8.1). In the case of the sustainability assessment using SCORE, the effects of the remediation alternatives were compared with a reference alternative. The reference alternative was defined as the site without remediation and with a closed chemical plant. All alternatives include excavation and disposal. However, the alternatives differed with regard to the remediation goals and the technology used for pre-treatment of excavated soils.

Alternative 1 represents remediation by excavation and disposal of all contaminated soil with concentrations above the generic guideline values for 'sensitive land use' according to the SEPA (2009b). Alternatives 2-4 represent remediation of all contaminated soil with concentrations above guideline values based on a site-specific risk assessment and taking into account the expected exposure conditions and environmental protection values at the site (Sweco, 2009).

Alternative 2 represents excavation and disposal of all contaminated soil with concentrations above the site-specific guideline values, whereas alternatives 3 and 4 represent excavation of all contaminated soil with concentrations above the site-specific guideline values combined with on-site pre-treatment and re-use of cleaned soil before disposal of the remaining contaminated soil. Alternatives 3 and 4 also include second analyses of contamination levels taken after excavation but before disposal, see Table 8.1.

Table 8.1 Remediation alternatives at the case study site

Alternative 1	Alternative 2	Alternative 3	Alternative 4
Excavation and disposal based on a simplified (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.

8.5. Results of the project risk assessment using PRA

The results described in this sub-chapter of the PRA apply to the Hexion site and follow the PRA method described in section 7.2.

Identification phase: sub-categories, risk events and consequences (Steps 1-2)

Structured brainstorming was used to achieve a consensus when identifying project-specific risk sub-categories associated with the seven project risk categories (Table 7.1) and the four alternatives (Table 8.1). This task was performed by two remediation experts. The main risk events and sub-risk events for each project risk sub-category were then identified, which also involved structured brainstorming by the same experts. Some of the risk events identified are general and some are alternative-specific.

Analysis phase: risk estimation, quantification and simulation (Steps 3-4)

Table 8.2 provides the project risk and risk sub-categories for all alternatives as well as an example of the results of a complete analysis (alternative 3) taken from a project risk sub-category, main risk events and sub-risk events (Step 1), through to a description of the consequences of each sub-risk event (Step 2) and an estimation of probabilities and consequences (Step 3).

Moreover, quantification in which 5^{th} and 95^{th} percentiles were estimated for the relevant probabilities (P) and economic consequences (C) was performed in this step. For situations where the experts were less uncertain of either the probability and/or the consequence, more narrow intervals were set. In the opposite situations, broader intervals represented higher degrees of uncertainty. Finally, simulation of the input data was carried out (Step 4).

Evaluation phase: tolerability, risk-mitigation measures (Steps 5-6)

The category and total project risks were calculated by means of a Monte Carlo simulation for each alternative. The mean values of the simulations are shown in Table 8.3. Alternative 1 has the highest total risk cost, whilst alternative 4 has the lowest total risk cost. On a detailed level, alternative 1 has the highest risk cost in five of the seven project risk categories with the exception of category 1.

Events related to *Technical basis for judgement and technical competence* (Category 5) account for the largest contribution to the total project risk cost for alternatives 1, 2 and 3. For details of how this result is achieved, see section 7.3 of this thesis. Alternative 4 is different in this respect since project risk category 7, *Other issues*, which includes costs linked to weather and break-ins, represents the largest risk cost. It is worth noting that project risk category 6, *Liabilities*, has not been considered in this assessment. No risks were found to be linked to liability issues due to the strict contract between NCC AB and Hexion regulating the questions regarding the contamination.

Table 8.2 Project risk categories and identified sub-categories for all assessed alternatives at Hexion. Main event, sub-risk event and consequences for alternative 3.

Project risk category	Project risk sub-category	Main event	Sub-risk event, 5th and 95th percentile of P (0,1)	Consequences, 5th and 95th percentile of C (€k)
(1) Remedial action	Problems with machinery			
	The remediation method contains 'risky' elements			
	Water treatment not working satisfactorily			
	Accidents in the neighbourhood			
(2) Authorities/ authorisation	Collaboration/communication with the authorities			
	Acceptance by the authorities			
(3) Concern and expectations	Concern among residents	Concern among local residents about the physical influences, such as dust spread in dry weather	Concern caused by external transport, P (0.1, 0.3)	Extra efforts in the form of covered platforms on trucks carrying hazardous and less hazardous waste to prevent dust spread C (36,900; 46,100)
			Concern about internal transport causing dust spread, P (0.2, 0.5)	Extra efforts to counter the spread of dust by using sweeping and salting C (4,100; 10,100)
			Concern about internal activities causing dust spread, P(0.2, 0.5)	Installation of a snow cannon to prevent dust spread C (5,500; 11,000)
(4) Project organisation and financial structure	Workers at the site have not received or embraced the instructions given			
	Lack of trust within the organisation – between the client and/or the environmental consultant and/or the contractor			
(5) Technical basis for judgement and technical competence	The defined contamination area is wrong			
	The defined contamination level is wrong			
	Misinterpreted hydrogeology			
	Unknown problems related to the ground but not the contamination content or contamination level			
(6) Liabilities	Previously unidentified contamination that has spread from the property			
(7) Other issues	Weather-related issues			
	Unexpected events at the remediation site			

Table 8.3 Risk costs in thousands of Euro (k€) and percentage of the total risk cost, divided into the seven project risk categories, for alternatives 1-4 in the Hexion case.

	Project risk categories														
	1		2		3		4		5		6		7		
Alternative.	Remedial action		Authorities Authorisation		Concern and expectations		Project organisation and financial structure		Technical basis for judgement and technical competence		Liabilities		Other issues		Total risk cost
	k€	%	k€	%	k€	%	k€	%	k€	%	k€	%	k€	%	k€
1	6	1	51	9	45	8	18	3	366	**66**	0	0	67	12	553
2	6	2	33	11	29	10	16	5	157	**54**	0	0	51	18	292
3	25	12	37	18	21	10	11	5	59	**29**	0	0	53	25	206
4	22	11	47	24	21	11	13	6	44	22	0	0	53	**26**	200

Figure 8.2 shows the histograms of the Monte Carlo simulations of the four alternatives. The higher and narrower the histogram, the more certain the experts are in their assessments, of the probabilities and consequences, of the events in question. Figure 8.2 indicates that the calculated risk cost for alternatives 2 and 3 is less uncertain than for alternatives 1 and 4. Alternatives 3 and 4 differ very little in terms of total risk cost although the associated uncertainty differs, with a slightly lower degree of uncertainty for alternative 3. There is, however, a greater probability that alternative 4 is the alternative with the lowest total risk cost compared with alternative 3. Alternative 2 has a very low probability whilst it is essentially zero for alternative 1. For details of how this probability is calculated, see Brinkhoff et al., (2014).

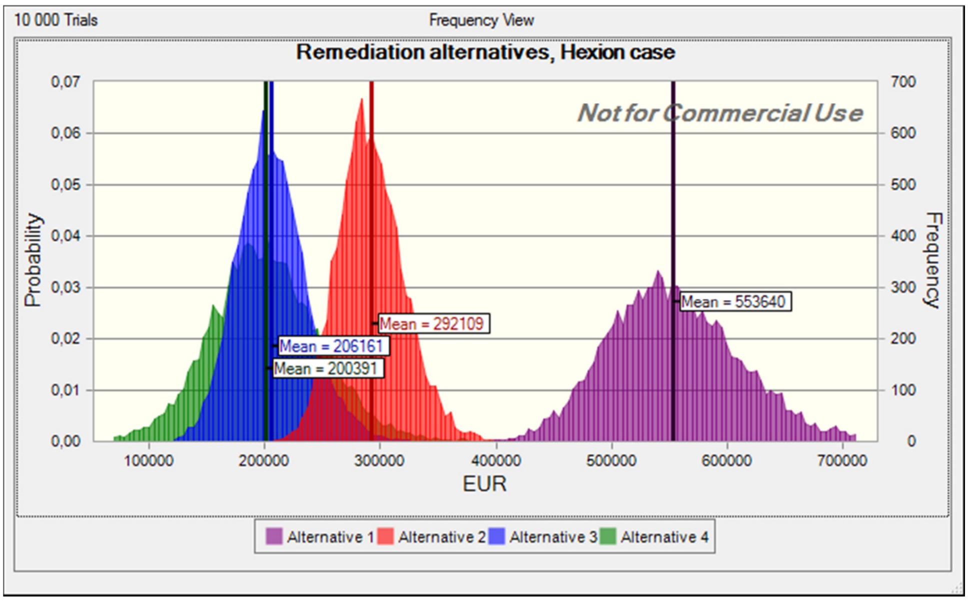


Figure 8.2 Total risk cost distributions for alternatives 1-4 at Hexion using Monte Carlo simulation.

The sensitivity analysis, contribution to variance analysis (Table 8.4), shows the contribution in percentage terms of each input variable (*C, P*) to the total variance of the resulting variable *(R)* for each alternative.

Table 8.4 Contribution to variance for the four remediation alternatives.

Alternative	**Contribution to variance (%)**			
1	35% (i)	19% (ii)	15% (iv)	10% (iii)
2	21% (i)	14% (iii)	13% (ii)	9% (v)
3	19% (i)	11% (ii)	11% (iii)	7% (v)
4	33% (vi)	24% (vii)	8% (i)	5% (iii)
Index	**Description of variable (Consequence or Probability)**			
(i)	The defined contamination area is found to be too small and additional soil needs to be excavated, transported and landfilled (C).			
(ii)	The probability that the defined contamination area is too small (P).			
(iii)	The authorities impose stricter demands due to public concern about the selected transport methods (C).			
(iv)	The estimated contamination level is wrong. The soil has been classified incorrectly using two contamination classes, resulting in additional landfill costs (C).			
(v)	At least two acts of sabotage in conjunction with break-ins, where pollution spreads to the soil and water resulting in extra time required for cleaning and additional landfill costs (C).			
(vi)	Soil washing cannot be employed for the intended material, resulting in additional landfill costs (C).			
(vii)	Soil washing cannot be employed for the intended material, resulting in a decrease in the cost of renting the washing equipment (C).			

Alternatives 1, 2 and 3 produce similar results with regard to the sensitivity analysis. The variables that contribute most to the overall uncertainty are misjudgement of contamination volume, the contamination level and issues relating to contact with the authorities. Contamination volume is included in alternative 4 although to a lesser degree than for the three other alternatives. The two largest input uncertainties for alternative 4 are associated with the soil-washing process.

In the final steps of the PRA, risk tolerability and risk-mitigation measures are evaluated. The five largest risk costs in the Hexion case study are shown in Table 8.5. The sum of the five largest risk costs for alternatives 1-4 are all greater than 65% of the total risk cost for each alternative.

Table 8.5 The five largest risk events in the Hexion case and the summed risk cost for these expressed in thousands of Euro (k€) and as percentage of the total risk cost for the alternative.

<table>
<tr><th rowspan="2">Five largest risk events</th><th colspan="8">Alternative</th></tr>
<tr><th colspan="2">1</th><th colspan="2">2</th><th colspan="2">3</th><th colspan="2">4</th></tr>
<tr><td>1</td><td colspan="8">The defined area of contamination is found to be too small due to uncertainties in the design.</td></tr>
<tr><td>2</td><td colspan="4">The estimated contamination level proves to be wrong, resulting in incorrectly classified soil.</td><td colspan="4">The authorities impose stricter demands due to uncertainties regarding public concern that the chosen method is disruptive (includes noise).</td></tr>
<tr><td>3</td><td colspan="4">The authorities impose stricter demands due to uncertainties regarding public concern that the chosen method is disruptive (includes noise).</td><td colspan="4">Difficulty separating soil due to frost.</td></tr>
<tr><td>4</td><td colspan="4">Difficulty separating soil due to frost.</td><td colspan="4">Remediation is required due to sabotage, which spreads contamination into the ground and/or water.</td></tr>
<tr><td>5</td><td colspan="4">Concern among neighbours with regard to transport to and from the site.</td><td colspan="2">Empty cisterns or drums in the ground not detected before remediation commenced.</td><td colspan="2">The authorities decide that the ongoing remediation method does not meet the requirements due to additional problems.</td></tr>
<tr><td>Summed risk cost</td><td>k€ 455</td><td>82%</td><td>k€ 207</td><td>67%</td><td>k€ 161</td><td>78%</td><td>k€ 164</td><td>82%</td></tr>
</table>

Tables 8.4 and 8.5 show that the first issue that needs to be addressed in order to reduce the probability and/or consequence, e.g. larger amounts of soil need to be excavated, is that the defined contamination area is incorrect. This event is the most uncertain input variable for alternatives 1-3 and the single largest risk cost for all four alternatives. Moreover, the consequences of acceptance by the authorities and the consequences of the contamination level being incorrect are relevant issues to address due to uncertain input variables. This analysis is true for at least alternatives 1-3 whereas alternative 4 has most uncertainty in the input variables for the soil-washing equipment and contamination area.

In conclusion, the results of the PRA reveal that alternative 4 is the best alternative, because overall it has the lowest total risk cost. Alternative 4 also has the highest probability of being the alternative with the lowest total risk cost compared with alternative 3, which is closest to alternative 4. However, it should be noted that alternatives 3 and 4 are very similar in terms of economic project risks. No further measures were taken in the application of the PRA method to the Hexion case study site as the PRA was performed after a remediation alternative was chosen and implemented at Hexion. The alternative selected for the remediation was Alternative 3.

If risk reducing measures were to be implemented, the following would be a desirable order in which to address the probability and /or consequences: 1) The defined contamination area is incorrect. This is the most uncertain input variable for alternatives 1-3 and the single largest risk cost for all four alternatives. 2) The consequences of the problem of acceptance by the authorities and the consequences of the contamination level being incorrect. This analysis is true for at least alternatives 1-3 whereas alternative 4 has the greatest uncertainty in the input variables for the soil-washing equipment and contamination area.

8.6. Result of the sustainability assessment using SCORE

SCORE allows a comprehensive analysis to be made of the remediation alternatives. It includes a wide range of input variables which require the involvement of different types of experts and stakeholders. . For the Hexion evaluation, remediation experts from government agencies, environmental economists etc. were involved. For information about how the SCORE method and the tool work and how to study the SCORE Hexion Case Study in detail, , see Rosen et al., 2014 (Paper III)and the SCORE manual (Anderson et al., 2014).

Environmental and social domains

In the case study the criteria and sub-criteria in the environmental and social domains were allowed to have varying degrees of influence on the total score and the weighting of the points. For key criteria in the environmental domain, soil was weighted highest with 23% while non-renewable natural resources had a weighting of 8%. The weighting between the domains was retained as the default value in the SCORE, i.e. 33% for each domain. The maximum weighting of the social domain was 23% for health and safety while the others were given an equal weighting of 15%. The sub-criteria weighting is determined by the number of sub-criteria that are relevant to the specific case. If all four are relevant, the weighting will be 25% for each and if no sub-criteria are relevant, a zero weighting is given and the weighting for the key criterion is used directly.

In the case study, not all the criteria are considered relevant. It is natural, for example, not to consider the impact on air with regard to source contamination, either on-site or off-site, as it is the remediation itself that impacts on air. The same applies to cultural heritage with regard to source contamination. Furthermore, this is the only one of the social criteria that was not considered relevant.

Table 8.6 shows the weighted key criteria for the environmental and social domains. No sub-criteria in E2 for all alternatives and in E4 and E5 for alternative 4 were awarded a score and hence these are not considered to be affected by any of the remediation alternatives. It can also be seen in Table 8.6 that the highest positive scores are in the social domain.

Table 8.6 Weighted scores for key criteria and ranking of alternatives in the environmental and social domains.

Domain/criteria	**Alternative**			
	1	**2**	**3**	**4**
Environmental domain	Weighted scores following MC simulation			
Soil (E 1)	0.44	0.53	0.53	0.59
Physical impact on flora and fauna (E 2)	0	0	0	0
Groundwater (E3)	0.56	0.29	0.29	0.29
Surface water (E4)	-0.02	-0.02	-002	0
Sediment (E5)	-0.18	-0.02	-0.02	0
Air (E6)	-0.68	-0.46	-0.38	-0.37
Non-renewable natural resources (E7)	-0.68	-0.38	-0.17	-0.07
Non-renewable waste generation (E8)	-0.62	-0.37	-0.15	-0.07
Weighted scores for the environmental domain for each alternative	**-1.01**	**-0.44**	**0.08**	**0.37**
Ranking in the Environmental domain	**4**	**3**	**2**	**1**
Social domain	Weighted score following MC simulation			
Local environmental quality and amenity (S1)	0.35	0.39	0.44	0.49
Cultural heritage (S2)	-0.09	-0.09	-0.09	-0.09
Health and safety (S3)	-0.02	0.09	0.09	0.15
Equity (S4)	0.70	0.51	0.51	0.51
Local participation (S5)	0.61	0.61	0.61	0.61
Local acceptance (S6)	0.91	1.06	1.13	1.20
Weighted score for the social domain for each alternative	**2.47**	**2.58**	**2.70**	**2.88**
Ranking in the Social domain	**4**	**3**	**2**	**1**

The total weighted score for the environmental and social domains with regard to the four alternatives shows that overall a much higher score is assigned to the social domain, see Table 8.6. This suggests that it is in this domain that the most positive effects of the remediation are expected and most of all for alternative 4. Note that alternative 1 and 2 got a negative weighted score in the environmental domain. From Table 8.6 shows that the ranking of alternatives, are the same for both domains, with alternative 4 emerging the best, followed by 3, 2 and 1.

Economic domain

The economic domain consists of the sub-items listed in Table 8.7. Table 8.7 shows the monetised values for each sub-item included in the CBA, both on the cost and the benefit side. The table also shows whether the sub-item was not considered to be of any relevance (NR) in the case study, or if it was of minor importance (X) and not monetised at all. Items that were considered important but were not possible to monetise are marked with X.

Table 8.7 shows the NPV, expressed as the expected value from Monte Carlo simulations, for the different remediation alternatives. Alternative 1 is the only alternative with an expected negative NPV value. Alternative 3 was the alternative with the largest expected NPV, followed by alternatives 2 and 4. This ranking is different from the environmental and social domains, where alternative 4 had the highest score followed by alternatives 3, 2 and 1.

Table 8.7 Most likely present values (PV) expressed in thousands of Euro (k€) C for benefit and cost items. NPV is the expected value following Monte Carlo simulation

Benefit item	**Alternative/Most likely present value (PV) in (k€)**			
	Alt. 1	**Alt. 2**	**Alt. 3**	**Alt. 4**
B1. Increased property value on site	5,363	5,363	5,363	5,363
B2a. Reduced acute health risks	nr	nr	nr	nr
B2b. Reduced non-acute health risks	0.033	0.033	0.033	0.033
B2c. Other types of improved health, e.g. reduced anxiety	8	8	8	8
B3a. Increased recreational opportunities on site	X	X	X	X
B3b. Increased recreational opportunities in the surroundings	(X)	(X)	(X)	(X)
B3c. Increased provision of other ecosystem services	(X)	(X)	(X)	(X)
B4. Other positive externalities	nr	nr	nr	nr
Cost item				
C1a. Costs for investigations and design of remedial actions	nr	nr	nr	nr
C1b. Costs for contracting	nr	nr	nr	nr
C1c. Capital costs due to allocation of funds to the remedial action	130	85	85	104
C1d. Costs for the remedial action, including transport and disposal of contaminated soil minus possible revenues of reuse of contaminants and/or soil	4,274	2,832	2,804	3,450
C1e. Costs for design and implementation of monitoring programs including sampling, analysis and data processing	1,024	1,024	1,024	1,024
C1fa. Project risks	501	265	187	181
C2a. Increased health risks due to the remedial action on site	92	92	92	92
C2b. Increased health risks due to transports to and from the remediation site, e.g. transports of contaminated soil	167	99	85	70
C2c. Increased health risks at disposal sites	nr	nr	nr	nr
C2d. Other types of impaired health due to the remedial action, e.g. increased anxiety	(X)	(X)	(X)	(X)
C3a. Decreased provision of ecosystem services on site due to remedial action, e.g. reduced recreational opportunities	(X)	(X)	(X)	(X)
C3b. Decreased provision of ecosystem services outside the site due to the remedial action, e.g. environmental effects due to transports of contaminated soil	62	38	36	34
C3c. Decreased provision of ecosystem services due to environmental effects at the disposal site	(X)	(X)	(X)	(X)
C4. Other negative externalities	nr	nr	nr	nr
Expected NPV (k€) after MC simulation	**-1,177**	**1,289**	**1,413**	**545**

A distributional analysis, Table 8.8, shows who is benefitting from of the remediation and who pays for it. These groups are marked EMP for employee, DEV for developer and PUB for the general public. It is clear that the developer benefits from the increase in market value. The largest cost items are in C1, i.e. costs for the remediation measure paid by the developer. It should be noted that the general public or rather the municipality could be the developer, i.e. the developer must not be a private company.

As regards employees, the greatest benefit is from the decrease in contamination, i.e. the health risk at the site is decreased. In all respects the greatest benefit of all alternatives is the increased land value. It is worth noting the benefits and costs marked X and (X), i.e. the items that were not possible to monetise. However, in the Hexion case it is sub-item B3a – Increased recreational opportunities on site – that was considered important but was not monetised. It could be argued that the value of the expected NPV could change slightly if B3a was monetised but not the ranking between the alternatives. No major changes in NPV would be expected since all the alternatives reduce the risks to an acceptable level for recreational use of the site.

Table 8.8 Distributional analysis of the expected ne tpresent value (NPV) result, expressed in thousands of Euro (k€), of the Hexion case.

	Alt. 1	Alt.2	Alt. 3	Alt. 4
NVP Benefit for Others	0	0	0	0
NVP Cost for Others	0	0	0	0
NVP Benefit for PUB	8	8	8	8
NVP Cost for PUB	-62	-38	-36	-34
NVP Benefit for EMP	0.033	0.033	0.033	0.033
NVP Cost for EMP	0	0	0	0
NVP Benefit for DEV	5,363	5,363	5,363	5,363
NVP Cost for DEV	-6,188	-4,408	-4,277	-4,922

The general public receives remediation benefits and are burdened with remediation costs, see Table 8.8. The greatest benefit for the general public is in B2c - reduced anxiety, and the highest costs are in C3b - environmental effects due to transport of contaminated soil. Moreover, there are no differences between the alternatives in terms of who benefits from the clean-up and who bears the costs. It should be noted that it is only in C1, costs for performing remediation, C2b, increased health risks due to transport to and from the remediation site, and C3b where the figures differ between alternatives. For information about the uncertainty estimate of the sub-items or other detailed information, see Söderqvist et al. (2014).

Sustainability score

A normalised sustainability score was calculated for each alternative, see Figure 8.3. This score is based on the sustainability score of three domains and shows which alternative is most likely to lead to sustainable development. For the Hexion case study site, it is alternative 4, i.e. excavation, sieving and soil washing, which have the highest sustainability score. As regards the other alternatives, the second-best alternative was 3, followed by alternative 2 and finally alternative 1. This ranking is the same as in the environmental and social domains but different to the economic domain.

The reason why alternative 1 is the least advantageous alternative is because it is the alternative that includes excavation and disposal of large amounts of material. This procedure is quite expensive. This is also shown in the CBA where alternative 1 is the only alternative with an expected negative NPV. However, there is uncertainty about this expected value (NPV) since not all cost and benefit items could be monetised.

Moreover, alternative 1 has a weighted score in the environmental domain that is negative, (-1.01), which means that the negative environmental effects of remediation are not balanced by the positive effects. The same is true for alternative 2, which also includes extensive excavation. In the social domain, the weighted score for alternative 1 is much higher but is still the lowest of all the assessed alternatives. The alternative that is most likely to contribute to sustainable development is alternative 4, which had the highest score in the social and environmental domains and also had a positive NPV.

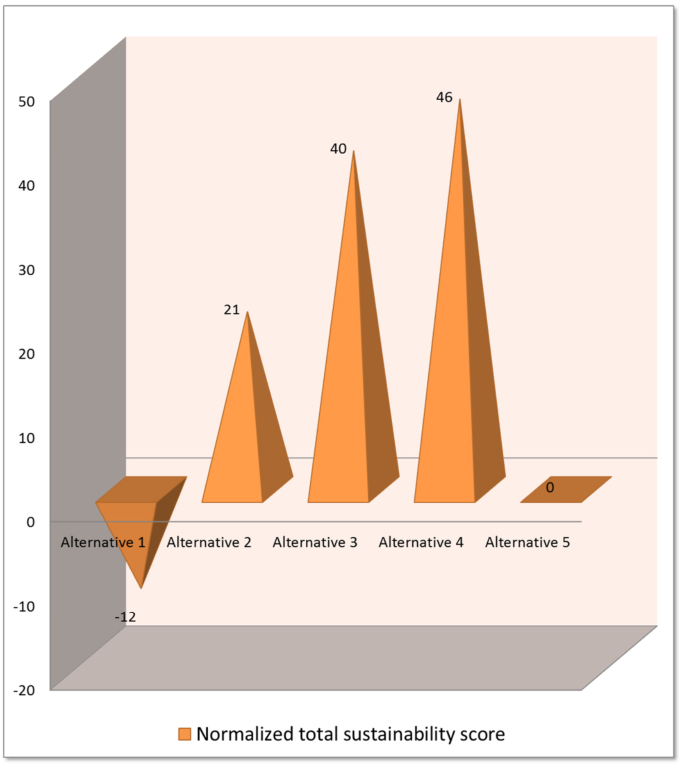


Figure 8.3 Normalised sustainability score for the four alternatives at Hexion.

8.7. Evaluation of PRA in the SCORE assessment

The results of the Hexion case study clearly show for all the alternatives that the risk cost for the four alternatives is the third-largest cost item after C1d - costs for remedial action, including transportation and disposal of soil, and C1e - costs for design and implementation of monitoring programmes. However, this does not change the order in which the alternatives are ranked after the CBA even though the PRA ranks the alternatives in the same order as the environmental and social domains. In the CBA, alternative 3 is ranked as the best (highest expected NPV) and the alternative that has the highest ranking in the environmental and social domain and in the PRA, alongside the sustainability score, alternative 4 is in third place, see Table 8.9.

Table 8.9 Ranking of alternatives in each domain, the PRA and the sustainability score.

	Ranking				
Alternative	Environmental domain	Social domain	Economic domain	PRA	Sustainability score
1	4	4	4	4	4
2	3	3	2	3	3
3	2	2	1	2	2
4	1	1	3	1	1

A substantially higher risk cost for the Hexion case than the one generated in the PRA would change the expected NPV from positive to negative. Unless a low expected NPV is compensated for in the other two domains, the risk cost could be crucial for sustainability ranking. In the Hexion case, the lower expected NPV for alternative 4 was compensated for by the environmental and social domains, hence it is ranked number 1 in the sustainability score, see Table 8.9.

It is not unrealistic to expect much higher risk costs than the figures used for Hexion. A possible reason for this could be that the contaminated soil volume has not been investigated sufficiently and it is therefore not precisely defined resulting in uncertainty about the volumes that need to be remediated. Another reason could be the use of a remediation method that is not widely used and hence there is uncertainty about whether remediation targets will be met. A third reason could be the use of other less well-developed methods, such as taking a percentage of the entire project cost and using it as a risk cost.

9. DISCUSSION

This chapter discusses the project risk assessment method as a standalone method and its use as part of the SCORE sustainability assessment method for assessing remediation alternatives.

9.1. PRA method

The suggested project risk assessment (PRA) method is based on the standardised approach to risk assessment according to ISO, and includes a set of project risk categories identified from a project owner's perspective. The PRA method is a probabilistic economic assessment of unexpected events, quantifying both the probabilities and consequences of such events, as well as accounting for uncertainties in these quantifications. The suggested method can be used for various remediation projects for a construction company. First is the case of remediation as part of construction work. For example, when the remediation is necessary before a redevelopment of a contaminated property and the contractor is responsible for the buildings as well. Secondly, when remediation in itself is the construction work, e.g. a public procurement of a remediation and the construction company is the contractor for the remediation only.

The optimum period for using the PRA method is in the early stages when a risk cost should be calculated for one or more remediation alternatives. The estimated risk cost can then either be enclosed with a tender and/or be used as decision support when choosing a specific type of remediation, or as part of an environmental due diligence process for a property. Moreover, it is possible to use the method during the course of a project, as suggested by the ISO standard for risk management (IS0, 2009), in order to work continuously on risk identification and mitigation. The stepwise design includes the iterative approach of the PRA method, which enables and supports the management of project risks by providing the user with input about their decision.

9.2. PRA tool

One of the strengths of the PRA method is the way in which uncertainties are taken into account. Estimations, in this case probabilities and economic consequences, are always associated with some degree of uncertainty. The PRA method deals with this by suggesting the use of a probability and consequence interval instead of assigning a point value. The statistical analysis of these input variables is handled using the add-in program Crystal Ball in the Excel-based tool.

The developed Excel-based PRA tool facilitates assessment of project risk cost calculations where there is uncertainty. It is possible to extract statistical data, e.g. mode, mean and percentiles, from the tool for use by the project risk assessment team and as a basis for communicating project risks to the decision-makers. Following Monte Carlo simulation, the tool provides information about the distribution of the risk cost for each alternative, category and sub-category and the largest risks for the assessed alternatives.

Moreover, the tool allows for each alternative to be analysed with regard to: (1) the uncertainty of the total project risk cost; (2) the probability of achieving the lowest risk cost; and (3) the contribution of each input variable to the total uncertainty of the project risk cost. These analyses (1-3) help the assessor to evaluate whether the uncertainty is acceptable or not and to rank alternatives and determine how likely it is that each alternative is the best with regard to project risk cost minimisation. The third analysis helps to decide which input variables to focus on in order to achieve a more reliable risk estimation.

9.3. Case study – application of the PRA

The PRA method was applied and illustrated by performing a case study for an area which is one of NCC's own property developments and where NCC has carried out remediation. The actual remediation was not influenced by the PRA although the development of the PRA method was influenced by the remediation. The definition of viable remediation alternatives and the expert judgement by the personnel involved in the remediation was based on the real case. The application in a case study was a way of refining the PRA method based on input from the operationalisation of the method and the tool.

The results from the case study show how the alternatives differ from each other and what they have in common in terms of project risks. The results show that the alternative that generates the largest amount of excavated material (alternative 1) had the highest risks cost. The reasons are primarily: 1) the large uncertainty regarding contamination volume; an uncertainty that is always a major risk in these kinds of projects. It also affects the risk cost most for the alternative that generates the largest amount of material that needs to be excavated and deposited. Secondly, the alternatives with a more detailed remediation design (alternatives 3 and 4) which included sieving and sieving and soil washing, were considered to be less uncertain when it came to certain unexpected events. The reason for this is that a more detailed design lowers the probability of an unexpected event. Examples of such events are disruptions or delays due to problems with the authorities.

In this case study the remediation alternatives were based on excavation but the PRA method has project risk categories that are general in scope. This means that the method can be used for other types of remediation methods, e.g. in-situ methods.

9.4. PRA in SCORE Sustainability Assessment

The suggested PRA method is a standalone method but is also part of the Cost-Benefit Analysis (CBA) in the SCORE method and tool for sustainability assessment (Söderqvist et al., 2014; Rosen et al., 2014).

Figure 9.1 shows the three domains of sustainability as viewed in SCORE with several detail layers. The economic domain, for example, has the PRA method in the centre as a visualisation of one part of what is evaluated in the CBA in order to calculate the social profitability, which is the unit of measurement in the economic domain. The aggregation of the three domains, i.e. the normalised sustainability score generated by the SCORE assessment, can be seen in the centre of Figure 9.1.

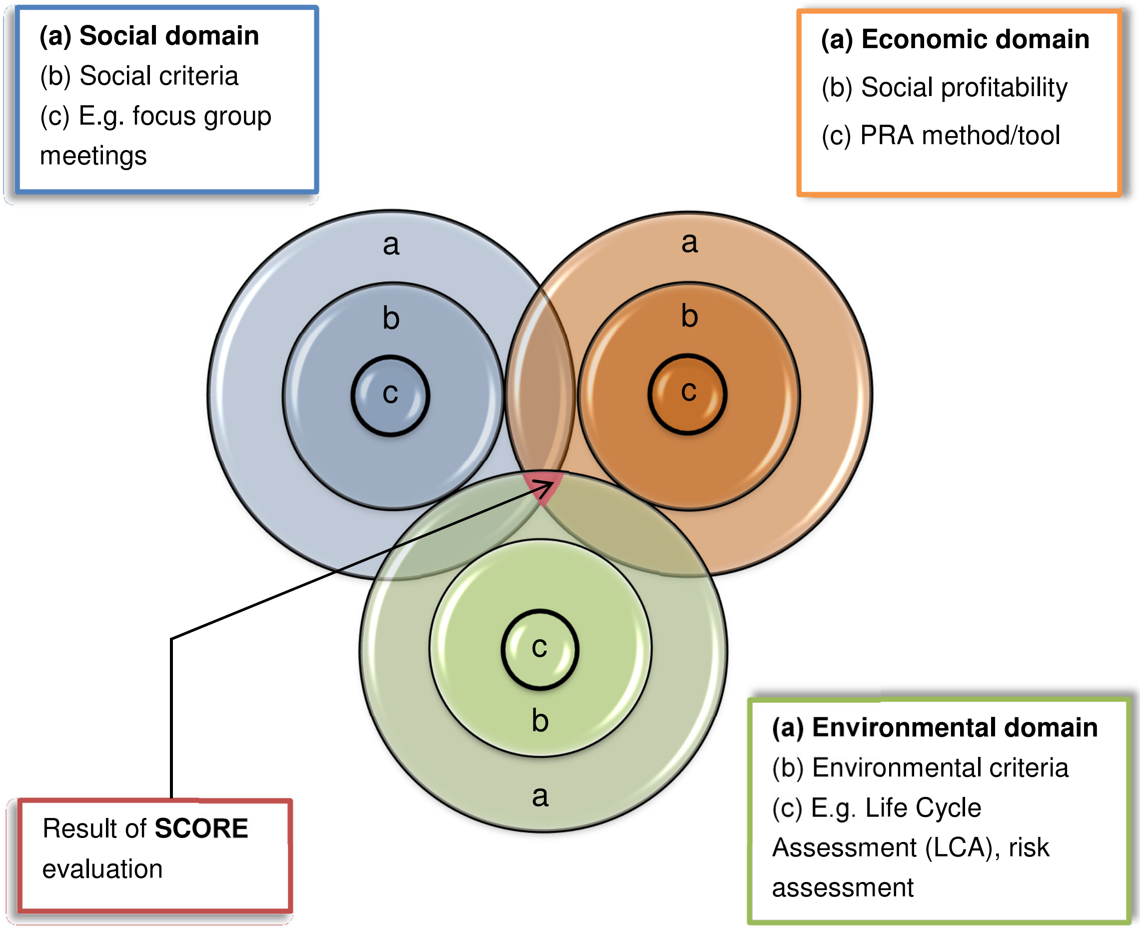


Figure 9.1 Sustainability domains with different layers.

The PRA result is used in the CBA and consequently in the broader sustainability analysis of SCORE. The PRA result is thus weighed together with the other parts of the sustainability assessment to form a comprehensive decision support material, see centre of Figure 9.1. Ness et al (2007) describe (Figure 4.3) seven tools for integrated prospective assessment able to handle nature-society systems in a single assessment. Five of those tools are used within the SCORE, (1) Conceptual modelling, (2) Multi-criteria analysis, (3) Risk analysis, (4) Uncertainty analysis and (5) Cost-benefit analysis

PRA and SCORE in construction projects

An assessment of project risks, such as the one carried out in the Hexion case study, provides the remediation design team with a great deal of information during project preparatory work. The PRA method can be used as a standalone method for economic assessment early on in a remediation project. The remediation in question can either be a part of a property development or part of another type of construction work. The result of the PRA can be a part of a tender as an amount to be added to a budgeted cost. It could also be used as in-house information and as a method for continuous management of risks during the project. However, it is also possible to use the PRA method as part of the sustainability assessment together with SCORE.

PRA as a tool and method follows exactly in terms of time and aim what SCORE is meant to be used for, i.e. as a decision aid and an opportunity to mitigate project risks and refine the remediation alternative with regard to the impact on the different domains. PRA and SCORE also follow in line with the current development of sustainability work by construction companies.

Environmental sustainability assessments in construction work have in the past focused mainly on buildings, i.e. by using certification systems such as BREEAM and LEED. However, development has also taken off in recent years with regard to sustainability assessments in other types of construction work, i.e. groundwork (including remediation). The CEEQUAL certification system was the first system on the market that focused on sustainability assessment of civil engineering projects. Others are being developed and of these SUNRA is an interesting contribution since it does not focus on the product but the process doing sustainable choices in a project.

On the other hand, BREEAM is about to launch a system known as BREEAM Infrastructure, which is in line with how CEEQUAL works. CEEQUAL and BREEAM are systems used to certify how well a project has dealt with environmental or sustainability issues throughout a project as well as the 'sustainability' of the project and company organisation. This is not done during the same time stage in which SCORE and PRA are expected to be used. A SCORE assessment is used earlier on in the process, as support when choosing a sustainable remediation alternative. Until now there has been a lack of detailed tools for such assessments that are able to take into account all sustainability domains. For construction companies, sustainability assessments of this nature can be useful in many ways, e.g. to achieve greater project efficiency by starting to think about the remediation design in detail early on in the process.

10. CONCLUSIONS AND FUTURE RESEARCH

In this final chapter the main conclusions are summarised and future research is suggested.

10.1. Conclusions

The following main conclusions were drawn from the work presented in this thesis:

- The PRA functions as a standalone method as well as a part of the sustainability assessment method SCORE. As a standalone method the PRA accounts for a financial analysis for the project owner and can provide important decision support in property business and development. For example, if the calculation or estimation of the expected risk costs is high, there might be a concern whether there is enough remedial cost space to go ahead with the purchase of a property. By using the PRA, an assessor can produce more accurate information on the existing risks, the expected risk cost, unacceptable risks and mitigating measures to lower probabilities or economic consequences of unexpected events. For a user of the PRA method, the PRA tool serves as a support and facilitates the assessment and the visualisation of the results.

- One of the strengths with the PRA method and tool is in regard to the management of uncertainties in the quantification of probabilities and consequences. By providing a possibility to put an interval of P and C which defines the chosen density function the resulting simulated risk cost can be examined in various ways. The statistical data that can be withdrawn from the simulation is of large help in identifying unacceptable risk events and by this identifying risk reducing measures that mitigates the risks. Afterwards it is possible to go back, by the iterative loop in the PRA method, and recalculated the risk cost with changed P and C for certain events.

- The PRA methods' stepwise working procedure means a well-structured way to work with project risks from identification, through analysis and to evaluation. The risk estimation by probabilistic risk analysis of unexpected events forms a sound base for decision support since it takes into account uncertainties. The method is hence beneficial to decision makers as well as to assessors. It serves as a structured and transparent base for communicating project risks.

- The identified project risk categories for remediation projects focus on the project owner's risks. Risks that can negatively impact the environment and humans as well as risks associated with externalities in the economic assessment are not included. This is in line with the aim of the project risk assessment, the CBA as used in SCORE, and the SCORE method. The use of the PRA in the Hexion case shows that this division is functional and serves its purpose.

! PRA and SCORE are in line with the construction companies' current development and work on sustainability issues. Certification systems like BREEAM and CEEQUAL handle the product that is constructed. However, they evaluate the degree to which a deliverable product fulfils a set of sustainability criteria. These methods do not aim to provide decision support by comparing the sustainability of different alternatives. This is where SCORE has an important role to play, providing an early estimation of sustainability of different remediation alternatives.

! It is important to know, as an assessor, which decision to support when selecting evaluation method to avoid an erroneous choice of method. The PRA, CBA and SCORE can be used by decision makers for several different decisions. A project owner might in one stage be more interested in a financial analysis but at another stage a sustainability analysis is what is sought after. With a supervisory authority the environmental and social domains in SCORE might function as a basis for communication.

10.2. Future research

The PRA method should be tested on other types of remediation projects that are not based on excavation. That would result in more information on sub-categories that can be used in future versions of the PRA method and tool.

The method has now been fully applied on only one case study. It is necessary to test the PRA method on a larger number of projects with other users to evaluate the robustness of the results provided by the method.

It would be interesting for further research to look into how the PRA method could be developed to be used for other types of construction projects than remediation projects. Such an adjustment and adaption would bring benefit to a larger amount of projects for the construction section since the number of remediation projects is relatively small compared to the total number of construction projects. This would be especially relevant for large infrastructure projects and the PRA could advantageously be used on such projects where the budgeted sums are large. The structured, transparent PRA method would give large benefits to the decision making team in these projects

It would be interest to, and highly relevant for a further development and adaptation of the PRA method to other types of civil engineering projects to examine what changes in organisation and project management that are necessary for the PRA method to be used. It would also be important to investigate what skills are needed to use and implement it.

Another interesting idea which in some sense is the same as for the PRA is to look into a modification of the SCORE method so that it is possible to evaluate the sustainability of other types of groundwork than remediation. This would be in line with the development of certification systems CEEQUAL, BREEAM Infrastructure and BREEAM Communities. These systems serve as a validation of a project and the continued development of PRA and SCORE would provide a tool that can contribute to sustainable decisions early in the process through its ability to do a comparative evaluation of different alternatives which would differentiate it from e.g. SUNRA.

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Paper I

In the submitted version some of the figures and tables were separated from the main text. To increase the readability, the figures and tables are here within the text

Economic project risk assessment in remediation projects prior to construction

– Methodology development and case study application

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Summary

Probabilistic economic analysis of project risks is not widely used in remediation projects. This paper presents a Project Risk Assessment (PRA) method to identify, quantify and analyze project risks in remediation projects. The suggested method is probabilistic and includes uncertainty analysis of input variables based on expert judgment. It is developed within a sustainability assessment tool called SCORE, but is also viable as a standalone tool for remediation projects. The method is applied on a case study: an old paint factory which is being redeveloped into a residential area. The PRA method is used to analyze and compare the project risks associated with four remediation options, all including excavation but with different degrees of on-site treatment. The result of the case study application shows which alternative has the lowest mean risk cost, the highest probability to have the lowest risk cost and how the risk costs are distributed, but also, importantly, helps the user to prioritize between risk-reducing measures.

1. Introduction

1.1. Background

"Remediation projects are often over budget and behind schedule." This statement, made by Diekmann in1997, is based on remediation projects carried out in the late 1990s. The reasons for cost increases and time delays were found to derive from the insufficiency of the project team to manage uncertainties. Tilford (2000) and Rao (1994) highlight the importance of being prepared for the unexpected by showing the cost increase in construction projects due, for example, to the unexpected presence of contaminants at the construction site. Knowledge and experience of remediation projects have improved since the 1990s and methods for assessing risks to humans and the environment have been further developed since then. However, the uncertainty and concern associated with the increased cost resulting from remediation measures are to a large extent still present and relevant (Wolf et al., 2012). There are a number of reasons why a remediation project is affected by cost increases. According to Havranek (1999), the causes derive from uncertainty in scope, quality of performance/technology, time and cost (expected/budgeted).

Diekmann (1997, 1998) distinguishes between the internal uncertainties of expected costs, i.e. uncertainties in budgeted costs, and the external uncertainties of incremental costs, i.e. costs associated with an unexpected event that occurs during the project. The latter is equivalent to the contingency concept used by Havranek (1999) and others. Contingency is the amount of money added to a cost estimate for the purpose of absorbing project risks. According to Havranek (1999), three main approaches are used to arrive at the contingency figure, i.e. the project risk cost: (1) percentage estimate, i.e. the project sum is increased by a percentage; (2) risk management approach, based on the process of identifying risk events, event probabilities and economic consequences; (3) computer modeling, i.e. some quantitative decision technique such as Monte Carlo simulation, decision tree analysis, and range estimations. These estimates of project risks or contingency requirements should be viewed in relation to budgeted costs, which are costs that will occur but with uncertainty regarding their level. Several papers focus on managing the uncertainties of the budgeted cost of remediation measures, e.g. Goldstein and Ritterling (2001), Selg et al. (2011) and Ram et al. (2013). Havranek et al. (2013) and Wolf et al. (2012) focus on uncertainties in both cost and time.

Project risk assessment is part of the risk management process, a standardized and widely accepted procedure. A comprehensive description of the risk management process can be found in the international standard issued by the International Organisation for Standardisation (ISO 31000: 2009). Similar frameworks have been presented by IEC (1995), AZ/NZS (2004 a, b) and the Swedish Civil Contingencies Agency (2003). A generic risk assessment process, as described in ISO 31000:2009, is

made up of several activities aimed at managing project risks and identifying measures to eliminate or minimize those risks. The procedure includes: (1) risk identification, which can be achieved through checklists, unstructured or structured brainstorming or methods such as Hazard and Operational Analysis (HAZOP) or Failure Modes and Effects Analysis (FMEA) (Burgman, 2005, Bedford and Cooke, 2001); (2) risk analysis, where risks are quantified or described qualitatively; and (3) risk evaluation, where an evaluation of the risk tolerability shows whether a measure is necessary or not.

Specific risk and cost management frameworks developed for cost engineers and energy projects include Framework from the Department of Energy (DOE, 2008), Total Cost Management Framework (TCM, 2012) and the ASTM Standard E2137 – 06 (2011) for estimating monetary cost and liabilities in environmental matters. Descriptions of Remediation Risk Management (RRM) frameworks are presented by SuRF-UK (2010), ITRC (2011), Rosén and Wikström (2005), Havranek (1999), among others. RRMs cover several issues, e.g. how to manage risks associated with (a) contamination, (b) uncertainty in remediation scope, (c) remediation goal realization, (d) uncertainty in budgeted costs, (e) unexpected events resulting in additional project costs (project risks) (Lemetrie, 2013).

Project risk assessment in soil remediation projects prior to construction commonly involves a qualitative or semi-quantitative assessment of probabilities and consequences for predetermined categories of risks and possibilities see e.g. Government of Canada (Gov. Canada, 2014). A semi-quantitative analysis can be used to make a rough assessment of the risk cost level by using fixed ranges of probabilities and economic consequences. The result provides support when deciding which risk reduction measures need to be taken and provides an approximate calculation of the total risk cost.

A quantitative risk assessment on the other hand quantifies the probabilities and consequences of unexpected events, with the possibility of including uncertainties in probabilities and consequences, thus making it possible to calculate a risk cost more accurately. Havranek (1999) concludes that it is possible, for the purposes of risk management, to express impacts on remediation scope, quality and time in monetary terms by e.g. making an advanced economic risk assessment, i.e. quantitative decision analysis. An economic risk assessment of unexpected and undesired events includes quantitative estimations of the probability of the event occurring and the economic consequences if the event does occur.

Diekmann (1997, 1998) presents a risk cost analysis method for use in remediation projects based on two different assessment methods employed to estimate uncertainties related to budgeted and incremental costs. Monte Carlo simulation is proposed to highlight the internal uncertainties of the budgeted cost along with an influence diagram to estimate external uncertainties, i.e. incremental costs. Mores (1993) suggests an analysis method estimating the contingency of remediation of environmental contamination at facilities operated by the U.S. Department of Energy. Lametrie (2013) presents an approach to implementing risk management in remediation projects to assist with the identification and quantification of uncertainties in remediation scope and to address project risk.

There is a demand from the construction industry for greater accuracy when assessing the cost of unexpected events associated with construction work (Taroun, 2013). McManus et al. (1996) emphasize that the same risk elements exist in remediation work as in regular construction work. It is thus reasonable to assume that there is a need for greater accuracy when assessing the cost of unexpected events associated with remediation. Such an assessment would provide an estimate of the costs to be added to the budgeted cost and provide the design and project team with improved decision support. An example of decision support could be determining which type of measure or combination of measures would be sufficient to reduce the risk of remediation costs running out of control due to unexpected events.

The project risk assessment approach of combining risk analysis with quantitative economic assessment methods, including uncertainty assessment, does not seem to be as widespread in the remediation sector as in other sectors. Such methods are common, for example, in the nuclear and chemical processing sector (Bedford and Cooke, 2001) and in oil and gas exploration (Havranek, 1999). There is thus a need to develop such a method for remediation projects.

1.2. Aim and objectives

The overall aim of this study was to develop a quantitative economic project risk assessment method (henceforth the PRA method) in line with the generally accepted risk management standard and an Excel-based computer tool to facilitate the assessment.

The specific objectives of this study were threefold: (1) to identify project risk categories; (2) to suggest a method for economic project risk assessment, including approaches for probability, consequence and uncertainty assessments; (3) to demonstrate an application of the suggested PRA method in a case study. Further, the potential use of the suggested PRA method within the SCORE tool for sustainability assessment of remediation alternatives is discussed (Söderqvist et al., (in prep.), Rosen et al., 2014).

1.3. Structure and scope of work

This paper is structured as follows: Section 2 describes the PRA method, the focus group discussion and the literature review carried out to identify project risk categories. Section 3 presents a case study application of the PRA method and the related results. In Section 4, the results, i.e. the suggested PRA method and practical examples, are concluded and discussed.

The suggested PRA method estimates project risk costs, i.e. additional costs for the owner of the construction project and thus not risks for other stakeholders, such as the general public.

The results from the focus group discussion and the literature review primarily focus on risks that occur in the implementation phase of a project, thus risks associated with the implementation of remedial measures. Excavation is the most common remediation method used in Sweden (Ländell, 2012), and specifically so in remediation projects prior to construction, due to technical excavation and a wish to avoid tying up money in the project over a long period. Therefore, focus is on excavation as the main measure, possibly in combination with methods such as sieving and soil washing, and thus the risk sub-categories have been designed primarily for these purposes.

2. Development of the project risk assessment method

Risk is commonly defined as the product of the probability of an unexpected event and the consequence of that event. In this study the following definition applies:

A project risk is the product of the probability that an unexpected event will occur while carrying out a specific remediation alternative and the economic consequence of that event for the construction project owner. The probabilistic risk cost is thus a possible but unexpected additional cost and not a result of the uncertainties of expected costs, i.e. budgeted costs.

2.2. Method

The starting point in the development of the PRA method was to identify project risk categories viable in remediation projects prior to construction, thus being general in scope and include all relevant project risks to support the project risk assessor. In order to identify project risk categories, results were compiled from a group discussion involving members of the remediation sector using a focus group technique, and also from a review of the literature on project risks related to remediation projects.

The purpose of focus group meetings is typically to learn about people's attitudes and opinions on a specific topic. It is a qualitative method and has been applied in disciplines such as social sciences, public health, anthropology among others (Wibeck, 2010). A semi-structured focus group meeting with representatives from different areas of the remediation sector (construction companies, consulting companies, local (real estate office) and regional (regulatory agency) authorities and a government research institute) was held to identify important project risk categories for construction companies. Risks were identified in three phases: (1) before land acquisition, (2) during selection of remedial action, (3) during implementation of the remediation.

A moderator was responsible for presenting the aim of the discussion and keeping the participants focused and a secretary made notes during the discussion. A summary of the discussion was circulated for review by the participating members as well as those invited but who were unable to attend. Five major project risk categories were identified: (1) authorities, (2) concern and expectations, (3) project organization and financial structure, (4) technical basis for judgment and technical competence, and (5) liabilities, see Exhibit 1.

The literature was reviewed to complement the focus group discussion. There was some difficulty identifying literature with well-developed risk categories for remediation projects. The literature review thus focused on two sources that have well-developed checklists of possible project risk categories. These sources are the Interstate Technology & Regulatory Council (ITRC) (2011), a comprehensive document in the area of risk management in remediation, and Rosén and Wikström (2005), a technical project risk analysis for BT Kemi, one of the largest and most costly remediation projects in Sweden. Unlike the focus group discussion, ITRC (2011) and Rosén and Wikström (2005) concentrated on project risks in publicly funded projects. Both sources present project risk categories that cover a wider range of areas, including environmental, social and economic aspects, compared to the focus group discussion, which concentrated on project risks for the project owner.

The approach used by ITRC (2011) is RRM, and the risk identification is divided into two phases – (1) before and (2) after selection of a remediation alternative. Project risk assessment and actions included in (1), which is the focus in this study, aim to support the decision by e.g. identifying the least 'risky' remediation alternative. The eight project risk categories put forward by ITRC are: (a) remedy performance, (b) regulatory, (c) political, geographic, social, (d) project schedule, staffing and financials, (e) legal, (f) human health, (g) environmental/ecological, and (h) economic, see Exhibit 1.

Rosén and Wikström (2005) presented a list of project risks compiled during a brainstorming session with remediation experts for three project phases: preparation, implementation and follow-up. The following six categories were identified: (i) remedial action excavation, (ii) social issues, (iii) work environment, (iv) environmental risk, (v) technical issues, and (vi) a mix of several areas, see Exhibit 1.

The categories identified in the focus group discussion differ in content to the analysis made by ITRC (2011) and Rosén and Wikström (2005) on risks associated with (a) remedy performance, (f) human health, (g) environmental/ecological and (h) economic and (i) the remedial action, i.e. excavation, (iii) work environment and the risks associated with machinery and vehicles, (v) technical issues, and (vi) a mix of several areas.

It is relevant to incorporate (a), (i), (iii), (v) and (vi) into the PRA, ideally included in a category covering remedial action, since risks associated with implementation of the remediation method could affect the efficiency of the remediation project. The remediation method could also put workers and their safety at risk and avoidance of this must be prioritized. The most commonly used remediation measure is excavation, which gives rise to risks involving machinery and vehicles and is included in the PRA categories. Since the categories (f) human health, (g) environmental/ecological, (h) economic and (v) environmental from ITRC (2011) and Rosén and Wikström (2005) aim to adopt a wider perspective of remediation and not simply focusing on project risks for the project owner, these categories are not included in this study. Yet another category is required, Other issues, which involves project risks that may be important but which do not fit into any of the existing categories. Examples include weather-related issues and break-ins. Weather-related issues were not mentioned by any of the three sources (Exhibit1) but identified by the authors as important to include due to e.g. effects on remediation efficiency. The suggested seven identified project risk categories (Exhibit 2) are based on the results from the focus group discussion with addition of the Remedial action category and the Other issues category, and are used as a basis for the PRA method.

Exhibit 1. Summary of project risk categories (bold letters) with examples.

Focus group discussion	ITRC (2011)	Rosén and Wikström (2005)
	Remedy performance (a) Selection of inappropriate remedy Technology feasibility Inappropriate objectives System failure	**Remedial action, excavation (i)** Excavation, loading and transport
Authorities (1) Communication between the contractor and the authority is not satisfactory	**Regulatory (b)** Changing regulations Emerging contaminants	
Concern and expectations (2) Concern among the general public regarding remediation	**Political, geographic, and social (c)** Preservation of historic landmarks Long-term land-use plans are changed Community perceptions	**Social issues (ii)** Usefulness of the action to the local community
Project organisation and financial structure (3) Recession Procurement process Distribution and logistics contracts do not favour the project	**Project schedule, staffing and financials (d)** Schedule issues Scope management Additional cost Quality failure Communication problems Contracting issues	
Technical basis for judgement and technical competence (4) Time delays Contaminant type, extent, changing amounts Leakage and spread of contaminants Lack of technical competence on the part of consultants		
Liabilities (5) A new contaminated area is found The remediation goal is not reached using the chosen remedial measure	**Legal (e)** Litigation Natural resource Damage claims	
	Human health (f) Changes in human health risk assessment Accidents (travel, transportation)	**Work environment (iii)** Incorrect delimitation of the working area Risks arising from contract work Sampling work is risky
	Environmental/ecological (g) Greenhouse gas emissions Energy consumption Risk to ecosystems, endangered species	**Environmental risk (iv)** Management of contaminated water Risks related to temporary landfill Waste management risks Waste water treatment plant
	Economic (h) Value of land use after remediation Economic consequences of delayed site closure Cost of delayed redevelopment	
		Technical issues (v) Electrical installation failure Recovery for planned land use Management of chemical products
		Mix of several areas (vi) Risks related to all activities involving use of machines and/or vehicles All tasks that might be risky

Remedial action

- The *remedial action* category aims to capture risks associated with a specific remediation method. Examples of risk events within this category could include the equipment, e.g. the sieving machine, and the soil material not working together or the equipment not working at all.

Authorities/authorisation

- The most important project risks related to *authorities* include communication between the contractor, the environmental specialist and the authority, which in most cases is the regulatory agency for the project.

Concern and expectations

- The *concern and expectations* category covers project risks associated with the concern experienced by the general public with regard to the remediation project. Examples of risks that could cause concern are the number of transport movements and dust and noise issues. This risk is present in the project from the beginning until the end and plays a central role.

Project organisation and financial structure

- A major project risk in all phases of a project is the way in which the public sector economy as a whole is developing. A recession might mean that it is not financially viable to build houses on the property and hence not to remediate. This risk is linked to the *project organisation and financial structure* category. Other risks in this category are the procurement process and distribution and logistics contracts. Logistics covers both off-site transport movements and on-site logistics.

Technical basis for judgment and technical competence

- Project risks in the *technical basis for judgement and technical competence* category are linked to various uncertainties regarding the contamination situation at the site in relation, for example, to contaminant type, extent and amount. Leakage and spread potential as well as not choosing the most cost-effective and time-optimal remedial measure are also included in this category. A poorly performed initial study, e.g. desktop and/or initial environmental soil survey, could be the root cause of the uncertainties. A suboptimal choice of remedial measure could also be a result of a lack of technical competence on the part of the consultants.

Liabilities

- Risks linked to matters related to *liabilities* are mostly present before the acquisition of a property. It could be relevant if a new contaminated area is detected on or close to the site during remediation. There is a further risk if the remediation goal is not achieved using the chosen remedial measure.

Other issues

- *Other issues* could include events linked to the weather situation, break-in and/or sabotage. It is possible to gather issues within this category that are not covered by other categories.

Exhibit 2. The seven suggested project risk categories from a company perspective, complete with explanations.

2.3. Result: the suggested PRA method and PRA tool

The suggested Project Risk Assessment (PRA) method is divided into six subsequent working steps, distinguished from each other in terms of aim and scope, see Exhibit 3. Sections 2.3.1 to 2.3.3 provide a more detailed description of the different steps. A computer tool is required to manage the analysis fully (Steps 3 and 4). Simulation of the total project risk using Monte Carlo simulation generates vast amounts of data and in this study an Excel-based tool has been developed where the Oracle Crystal Ball add-in program is used for simulations (below termed the PRA tool).

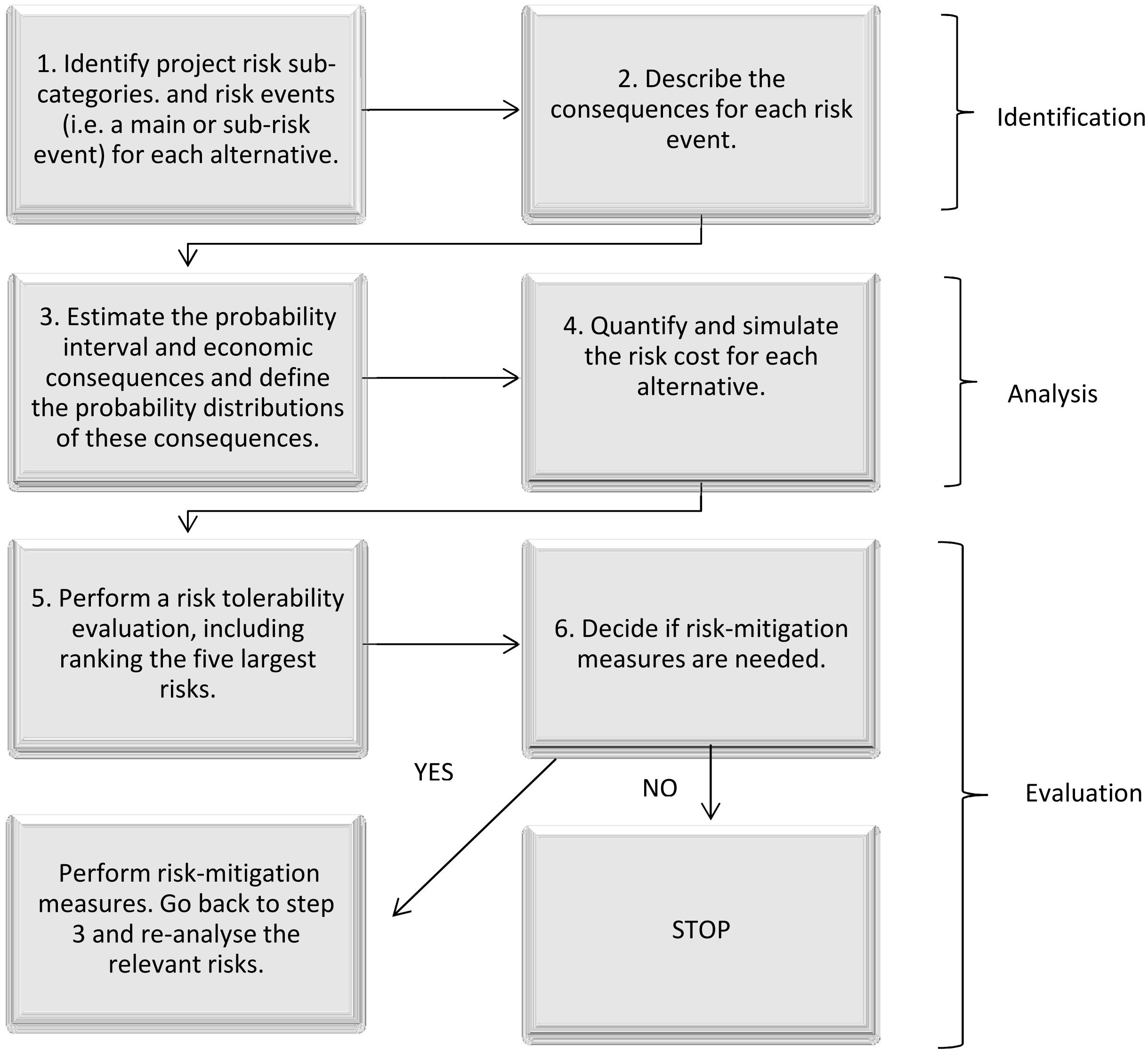

Exhibit 3: Description of the suggested step-by-step PRA method.

2.3.1. *Identification phase: sub-categories, risk events and consequences (Steps 1-2)*

A number of methods are available to obtain information about the risks present in a project, such as the Delphi method, Failure Modes and Effective Analysis (FMEA), Hazard and Operational Analysis (HAZOP) and brainstorming sessions (see e.g. Bedford and Cooke, 2001; Aven, 2003; Burgman, 2005). In the PRA method described here, it is suggested that structured brainstorming sessions with experts are used to identify risk sub-categories and risk events associated with project risks by using the project risk categories (Section 2.1, Exhibit 2) as a starting point. Structured brainstorming encourages participation and builds on the ideas of others by every member contributing to the discussion (Burgman, 2005). It is suggested that risk sub-categories and risk events are identified for one remediation alternative at a time.

Just as there may be sub-categories of project risks, an event – the main event for example – could be divided into sub-events. Risk events can result in either negative (costs) or positive (possibilities) consequences. A description of the consequences associated with each identified main or sub-risk event is also prepared. Consequences can be described in terms of additional working days, additional consulting time or additional transport and landfill fees but they must be possible to monetize.

2.3.2. *Analysis phase: risk estimation, quantification and simulation (Steps 3-4)*

The estimation of the probability of risk events and the uncertainty of the economic consequences should be carried out by experts with experience of remediation projects similar to the project under consideration. A project risk (*R*) is defined here as the product of the probability (*P*) and the negative or positive consequences (*C*) of an unexpected event (*i*) occurring during remediation. Eq. 1 denotes the risk calculation:

$$R_i = P_i * C_i \qquad \text{(Eq. 1)}$$

It is common to use experts to estimate probabilities (*P*) and consequences (*C*) in probabilistic risk analysis (Bedford & Cooke, 2001) since 'real data' can be difficult or impossible to find due to the uniqueness of the project. To manage and express the experts' uncertainty in their estimation of *P* and

C of events occurring, both *P* and *C* are expressed with an uncertainty interval. In the PRA tool the interval range assigned by the user is between the 5^{th} percentile representing the lowest reasonable value and 95^{th} percentile representing the highest reasonable value. This implies that 90% of all possible probabilities and economic consequences fall within this range.

The probability density functions are chosen based on what is suitable for the type of data at hand. In the PRA tool, it is recommended that uncertainties in *P* are represented by means of a beta distribution which often is used to represent variability over a fixed range (Moitra, 1990), e.g. a probability interval with range [0, 1]. Uncertainties in economic entities such as *C* are often represented by means of a log-normal distribution (Bedford and Cooke, 2005). After this, the mean risk cost for each project risk and project risk category is calculated in the quantification step.

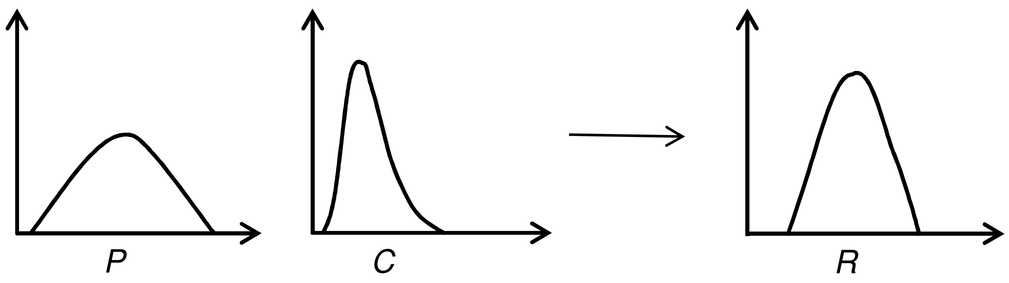

Exhibit 4. Illustration of how Monte Carlo simulation is used to include uncertainty in the input variables (P and C) and the resulting project risk (R).

Monte Carlo simulation randomly selects values from the density functions for *P* and *C* a large number of times – 10,000 times for example – to generate a resulting histogram of *R*. The outcome is a probability distribution of the economic value of a project risk for specific events, the project risk categories and the total project risk cost for each alternative (Eq. 2) with associated uncertainties (Exhibit 4).

$$R_a = \sum_{i}^{N} \sum_{k}^{K} P_{i,k,a} C_{i,k,a} \qquad \text{(eq. 2)}$$

R_a = Total project risk for alternative a (a= 1,.., A) for events i (1,…,N) and categories k (1,…,K)
P = Probability
C = Economic consequence

Monte Carlo simulation makes it possible to extract statistical parameters, such as mode, mean and percentiles, and allows each alternative to be analyzed with respect to e.g.: (1) the uncertainty of the total project risk cost; (2) the probability of having the lowest risk cost (3) the contribution of each input variable to the total uncertainty of the project risk cost. The first analysis helps to evaluate whether the uncertainty is acceptable. The second analysis helps to rank alternatives and to determine how likely it is that each alternative is the best with regard to project risk cost minimization. The third analysis helps to decide which input variables to focus on in order to achieve more reliable risk estimation.

2.3.3. *Evaluation phase; tolerability, risk-mitigation measures (Steps 5-6)*

In the final steps it is decided whether any project risks are unacceptable and should be reduced. This procedure is project-specific as every organization has limits on how large an economic risk is acceptable for different project types, i.e. depending on the size and scope of the project. However, in the PRA tool the five largest risk costs are identified and together with the sensitivity analysis it is believed to provide a sufficient overview of where measures should be taken. Another type of identification of large risk costs could be the use of a threshold value for *P*, *C* and/or *R*. For project risks that are unacceptable, measures are taken, and accounted for in cost calculations. The procedure starts again in Step 3 by estimating new probabilities and/or consequences as part of an iterative loop.

3. Case study application

3.1. The Hexion site

The former paint manufacturing company Hexion is located in the Gothenburg area in south-west Sweden and has a history of paint production that dates back more than 100 years. The site is located in an area of complex glacial geology, including terminal moraine deposits. Investigations and a risk assessment of soil and groundwater showed unacceptable contamination risk levels for humans and

ecosystems with regard to lead, softeners (DEHP), aromatic and aliphatic hydrocarbons and polyaromatic hydrocarbons (PAHs). The plan is to transform the site into a residential area with a metropolitan character, complete with housing, office/commercial buildings, pre-school, green spaces with playgrounds and parking facilities.

To prepare for the construction of new buildings and infrastructural installations, substantial amounts of soil need to be removed. All four remediation alternatives (Exhibit 5) include excavation and disposal. However, the alternatives differ with regard to (1) remediation objectives, resulting in variations in the amounts of excavated soil and (2) the technology used for pre-treatment of excavated soils. Moreover, alternative 3 and 4 include a second round of analyses of contamination levels after excavation, before disposal.

Alternative 1

- Excavation (91,100 metric tonnes) and disposal based on a generic risk assessment.

Alternative 2

- Excavation (57,200 metric tonnes) and disposal based on a site-specific risk assessment.

Alternative 3

- Excavation (57,200 metric tonnes), sieving and disposal based on a site-specific risk assessment.

Alternative 4

- Excavation (57,200 metric tonnes), sieving, soil wash and disposal based on a site-specific risk assessment.

Exhibit 5. Remediation alternatives at the Hexion case study site.

3.2. Project risk assessment

The first three steps in the PRA were performed by a group of experts consisting of two remediation experts and a site manager. Structured brainstorming was used, by the two remediation experts, to reach a consensus when identifying project-specific risk sub-categories (Exhibit 6) associated with the seven project risk categories (Exhibit 2) and four alternatives (Exhibit 5). .

Exhibit 6. Project risk categories and identified sub-categories for all assessed alternatives at Hexion.

Project risk category	Project risk sub-category
Remedial action	Problems with machinery
	The remediation method contains 'risky' elements
	Water treatment not working satisfactorily
	Accidents in the neighbourhood
Authorities/authorisation	Collaboration/communication with the authority
	Acceptance by the authority
Concern and expectations	Concern among residents
Project organisation and financial structure	Workers at the site have not received or embraced the instructions given
	Lack of trust within the organisation between the client and/or an environmental consultant and/or the contractor
Technical basis for judgement and technical competence	The defined contamination area is wrong
	The defined contamination level is wrong
	Misinterpreted hydrogeology
	Unknown problems related to the ground but not the contamination content or contamination level
Liabilities	Previously unidentified contamination that has spread from the property
Other issues	Weather-related issues
	Unexpected events at the remediation site

The main risk events and sub-risk events for each project risk sub-category and each alternative were then identified, which also involved structured brainstorming by the same experts. Some of the risk events are general but some are alternative-specific. Exhibit 7 provides an example of the results of a complete analysis (alternative 3) from a project risk sub-category, main risk events and sub-risk events (Step 1) through to a description of the consequences of each sub-risk event (Step 2) and estimation of probabilities and consequences (Step 3).

The main risk event here is the concern of the residents in the area as a result of the spread of dust in dry weather, with sub-risk events defined as spread of dust due to (a) transportation off site and/or (b) transportation on site and/or internal activities. The identified consequences of risk events focus on capturing the monetary impact on the project owner. The consequences are described in terms of extra effort to mitigate dust spread, which is transformed into unexpected costs in the quantification step. For each risk event, an interval representing the 5th and 95th percentiles was estimated for the relevant probabilities (P) and economic consequences (C). For situations where the experts were relatively certain of the estimation, narrow intervals were set. In the opposite situations, the intervals were broader. In the estimation of probabilities and economic consequences, the experts' individual estimations were used, i.e. the experts estimated different items. Thereafter, simulation of the input variables is carried out (Step 4).

Exhibit 7. Example from the project risk assessment at Hexion for alternative 3.

Step 1				**Step 2**	**Step 3**	
Project risk category	Project risk sub-category	Main risk event	Sub-risk event	Consequence	5th and 95th percentile of P (0,1)	5th and 95th percentile of C (k€)
(3) Concern and expectations	Concern among local residents	Concern among local residents about the physical influences, such as dust spread in dry weather	Concern caused by external transport	Extra efforts in the form of covered platforms on trucks carrying hazardous and less hazardous waste to prevent dust spread	0.1, 0.3	36.900, 46.100
			Concern about internal transport causing dust spread	Extra efforts to counter the spread of dust by using sweeping and salting	0.2, 0.5	4.100, 10.100
			Concern about internal activities causing dust spread	Installation of a snow cannon to prevent dust spread	0.2, 0.5	5.500, 11.000

3.3. Results of a case study application of the PRA method at Hexion

The category and total project risks were calculated by means of a Monte Carlo simulation for each alternative, shown in Exhibit 8 as the mean value. Alternative 1 has the highest total risk cost, whilst alternative 4 has the lowest total risk cost. It can also be seen in Exhibit 8 that alternative 3 is very close to alternative 4, differing by just 6k€. Exhibit 8 also contains information on a detailed level, i.e. the mean value of the risk cost of the project risk categories for each alternative. Alternative 1 has the largest risk cost in five of the seven project risk categories, with the exception of category 1, compared with the three other alternatives. Events related to *Technical basis for judgment and technical competence* (Category 5) account for the largest contribution to the total project risk cost for alternatives 1, 2 and 3.

Alternative 4 is different in this respect since project risk category 7, *Other issues*, which includes costs linked to weather and break-ins, accounts for the largest risk cost. It is worth noting that project risk category 6, *Liabilities*, has not been considered in this assessment. No risks were found to be linked to liability issues.

Exhibit 8. Risk costs, total and divided into categories, for alternatives 1-4..

Project risk categories															
	1		2		3		4		5		6		7		
Alternative no.	Remedial action		Authorities Authorisation		Concern and expectations		Project organisation and financial structure		Technical basis for judgement and technical competence		Liabilities		Other issues		Total risk cost
	k€	%	k€	%	k€	%	k€	%	k€	%	k€	%	k€	%	k€
1	6	1	51	9	45	8	18	3	366	**66**	0	0	67	**12**	553
2	6	2	33	11	29	10	16	5	157	**54**	0	0	51	**18**	292
3	25	12	37	18	21	10	11	5	59	**29**	0	0	53	**25**	206
4	22	11	47	**24**	21	11	13	6	44	22	0	0	53	**26**	200

Exhibit 9 shows the result with associated uncertainties. The higher and narrower the curve, the more certain the experts are in their assessments with regard to the probability and consequence of the assessed events. Exhibit 9 indicates that the calculated risk cost for alternatives 2 and 3 is less variable than for alternatives 1 and 4. Alternatives 3 and 4 differ very little in terms of total risk cost although the associated uncertainty differs, with a slightly lower uncertainty for alternative 3. On the other hand, Exhibit 10 shows that alternative 4 has the highest probability (around 0,50) of being the alternative with the lowest total risk cost compared with alternative 3 (around 0,40). Alternative 2 has a very low probability whilst it is essentially zero for alternative 1.

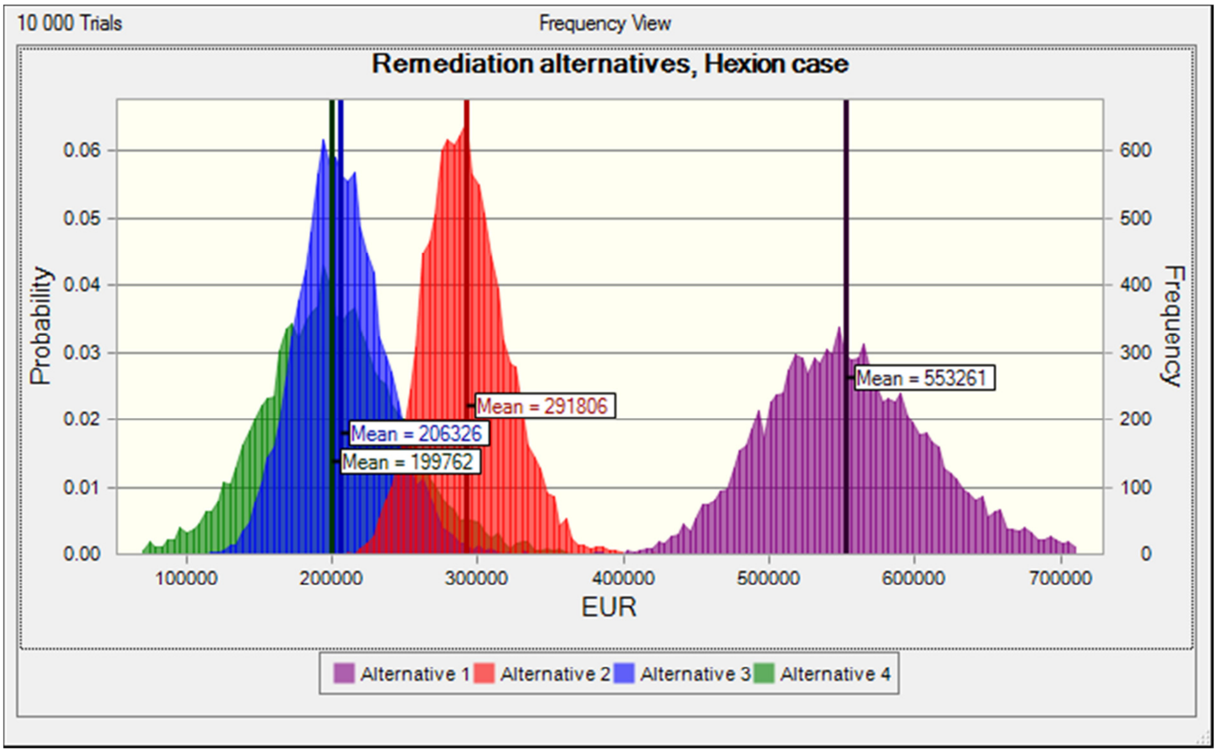

Exhibit 9. Distribution of total risk cost alternatives 1-4 following Monte Carlo Simulation.

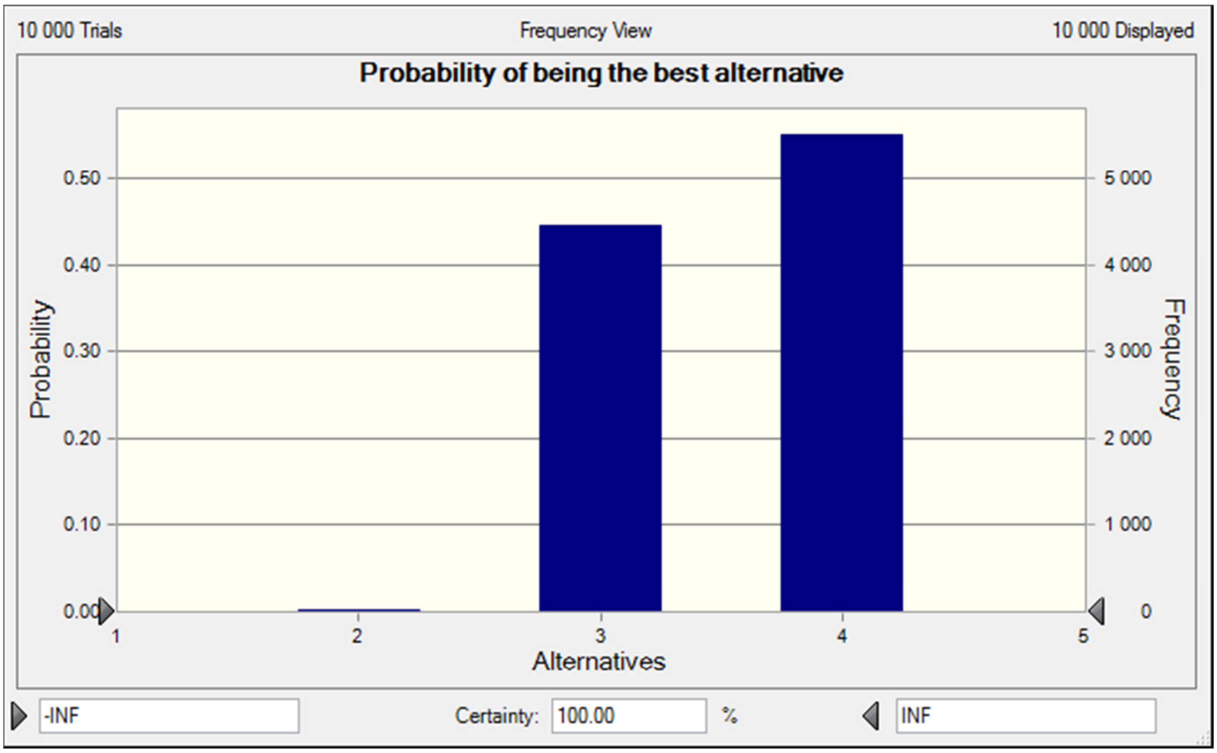

Exhibit 10. The probability of having the lowest risk cost, alternative 1-4.

A sensitivity analysis was made in the form of a contribution to variance analysis, see Exhibit 11. The analysis shows the contribution in percentages from each input variable (*C*, *P*) to the total variance of the resulting variable, in this case the total risk cost of the alternative.

Exhibit 11. Contribution to variance for the four remediation alternatives.

Alternative	***Contribution to variance (%)***			
1	*35% (i)*	*19% (ii)*	*15% (iv)*	*10% (iii)*
2	*21% (i)*	*14% (iii)*	*13% (ii)*	*9% (v)*
3	*19% (i)*	*11% (ii)*	*11% (iii)*	*7% (v)*
4	*33 % (vi)*	*24% (vii)*	*8% (i)*	*5% (iii)*
Index	***Description of variable (Consequence or Probability)***			
(i)	*The defined contamination area is found to be too small and additional soil needs to be excavated, transported and landfilled (C)*			
(ii)	*The probability that the defined contamination area is too small (P)*			
(iii)	*The authority imposes stricter demands due to public concern about the selected transport methods (C).*			
(iv)	*The estimated contamination level is wrong. The masses have been classified incorrectly using two contamination classes, resulting in additional landfill costs (C).*			
(v)	*At least two acts of sabotage in conjunction with break-ins, where pollution spreads to the soil and water resulting in extra time required for cleaning and additional landfill costs (C).*			
(vi)	*Soil washing cannot be used for the intended material, resulting in additional landfill costs (C).*			
(vii)	*Soil washing cannot be used for the intended material, resulting in a decrease in the cost of renting the washing equipment (C).*			

Alternatives 1, 2 and 3 have similar results with regard to the sensitivity analysis. The variables that contribute most to the total uncertainty are misjudgment in contamination volume, the contamination level and issues relating to contact with the authority. Contamination volume is included in alternative 4 although to a lesser degree than for the three other alternatives. The two largest in-put uncertainties for alternative 4 are associated with the soil-washing process.

In the final steps of the PRA, risk tolerability and risk-mitigation measures are evaluated. The five largest risk costs in the Hexion case study are shown in Exhibit 12. The sum of the five largest risk costs for alternatives 1-4 are all greater than 65% of the total risk cost for each alternative.

Exhibit 12. The five largest risk events in k€ and % of the total risk cost.

Five largest risk events	**Alternative no.**							
	Alt 1		Alt 2		Alt 3		Alt 4	
1	The defined area of contamination is found to be too small due to uncertainties in the design.							
	205 k€	37%	81 k€	26%	81 k€	39%	81 k€	41%
2	The estimated contamination level proves to be wrong, resulting in incorrectly classified soil.				The authority imposes stricter demands due to uncertainties regarding public concern that the chosen method is disruptive (includes noise).			
	132 k€	24%	52 k€	17%	31 k€	15%	31 k€	15%
3	The authority imposes stricter demands due to uncertainties regarding public concern that the chosen method is disruptive (includes noise).				Difficulty separating soil due to frost.			
	49 k€	9%	31 k€	10%	26 k€	13%	26 k€	13%
4	Difficulty separating soil due to frost.				Remediation is required due to sabotage, which spreads contamination to the ground and/or water.			
	42 k€	8%	26 k€	9%	14 k€	7%	14 k€	7%
5	Concern among neighbours with regard to transport to and from the site.				Empty cisterns or drums in the ground not detected before remediation commenced.		The authority decides that the ongoing remediation method does not meet the requirements due additional problems.	
	27 k€	4%	16 k€	5%	9 k€	4%	12 k€	6%
Total	455 k€	82%	207 k€	67%	161 k€	78%	164 k€	82%

For alternatives 3 and 4, the risk costs associated with erroneous estimations of the amounts of contaminated soil are compensated by the possibilities for soil re-use since the sieving process and second analyses result in larger amounts that can be reclassified as being less contaminated. No such possibility has been identified for alternatives 1and 2.

Exhibit 11 and 12 shows that measures to reduce the probability and/or consequence that the defined contamination area is incorrect should be the first issue to address since it is the most uncertain item of input variable for alternatives 1-3 and the single largest risk cost for all four alternatives. Moreover, the consequences of the problem of acceptance by the authority and the consequences of the contamination level being incorrect are relevant issues to address due to uncertain input variables. This analysis is true for at least alternatives 1-3 whereas alternative 4 has most uncertainty in the input variables for the soil-washing equipment and contamination area. In conclusion, it is alternative 4 that is the best alternative because overall it has the lowest total risk cost and the highest probability of being the alternative with the lowest total risk cost compared with alternative 3, which is closest to alternative 4.

4. Discussion and Conclusions

Controlling authorities requires thorough assessments as a basis for reaching decisions about risk reducing measures at contaminated sites. In cases where a private construction company is the contractor and carries out the remediation there are strict demands from the controlling authority and from in-house environmental consultants to achieve acceptable risk levels for humans and the environment. The construction company board, on the other hand, has also other types of demands. Those who design the project need to present a remediation alternative that does not jeopardize the company in any way, i.e. impose unacceptable economic risks. In this situation the need for accurate figures for additional costs and thus the size of the contingency for unexpected events, expressed in kronor, dollars or euro, is crucial. The transparency of such an assessment is of major importance to the assessor as well as the decision-maker as a means of communication. The PRA method described in this paper meets these requirements.

The suggested six-step probabilistic method for quantification of project risks follows the standard for risk management (ISO 31000: 2009), from identification of risks through to implementation of measures to mitigate risks. The method allows the user to manage the unique risks of any remediation project by showing how to analyze and evaluate risk events that may lead to additional unexpected costs for the project. The PRA method provides guidance on how to assess risks that are unacceptable and a sensitivity analysis that shows what accounts for the largest contribution to the total uncertainty in the project risk costs. The PRA method described in this paper can be part of a Cost-Benefit Analysis (CBA) but can also function on its own as a decision support tool and as a tool to manage project risks associated with remediation. It can also be used to support decisions regarding design and/or choice of remediation alternative.

The PRA method was originally developed to be part of the SCORE method for sustainability assessment of remediation alternatives using Multi-Criteria Decision Analysis (MCDA), see e.g. Brinkhoff (2011) and Rosén et al. (2014). Assessments of the sustainability of remediation projects or different remediation alternatives are high on the agenda nationally and internationally (Bardos et al., 2011; Swedish EPA, 2009; Surf-UK, 2010; NICOLE, 2012). A variety of tools are available on the market that are capable of assessing the environmental impact or sustainability of remediation alternatives, e.g. Sustainable Remediation Tool (SRT) (Ferdos and Rosén, 2013) developed by AFCEE, GoldSet (Witton, 2009) or point-scoring systems such as BREEAM, LEED (NICOLE, 2012) and CEEQUAL (CEEQUAL, 2012). The SCORE tool is based on MCDA (Rosén et al., 2014) and is designed to provide decision support when choosing from a set of remediation alternatives. The quantification of project risks in monetary terms shows additional costs due to unexpected events and is suggested to be part of the cost analysis in the CBA in the economic domain where the internal remediation costs for the contractor are assessed (Rosén et al., (2014); Söderqvist et al. (in prep.)). In Exhibit 14 it is shown where the PRA method fits in the CBA in the SCORE method.

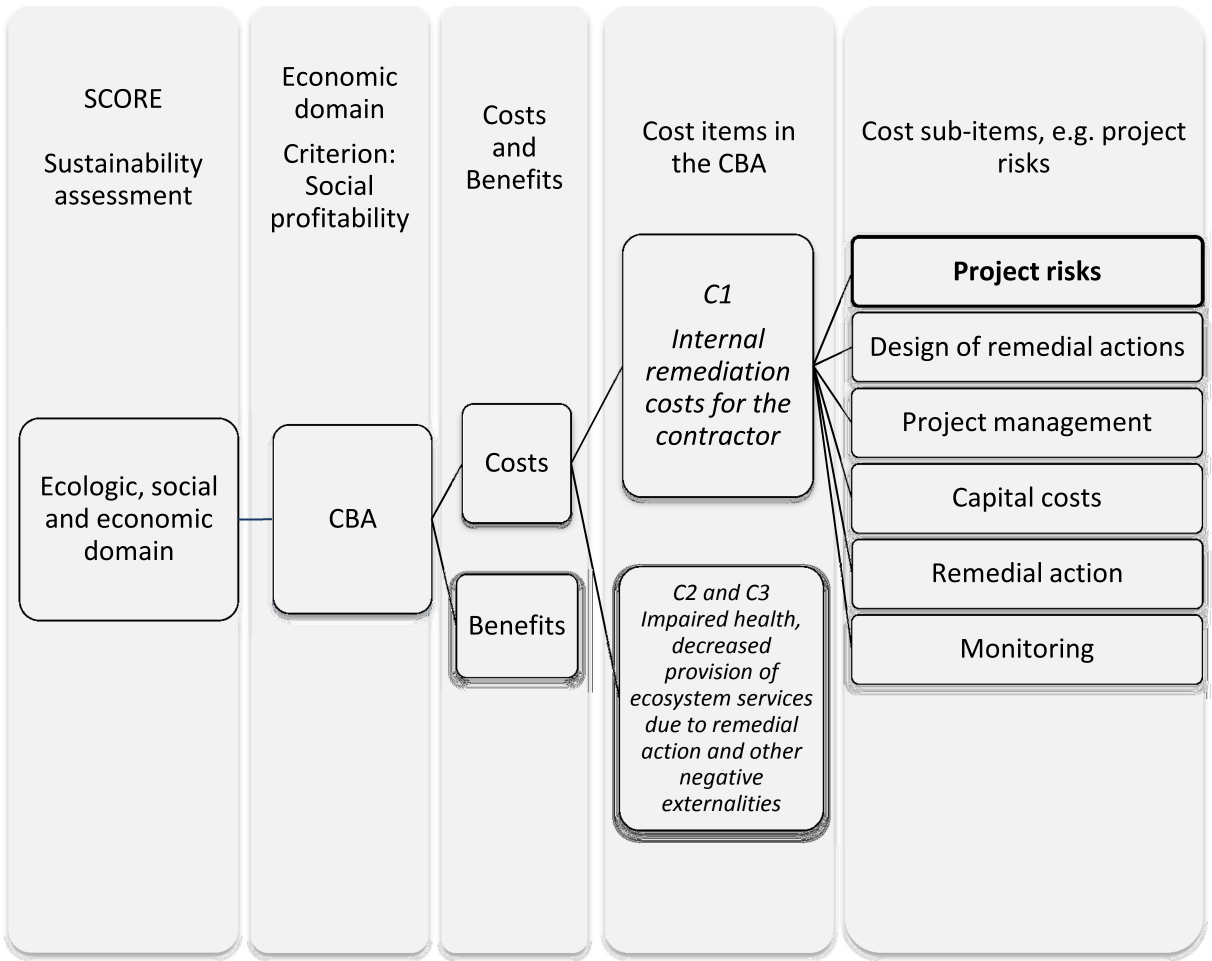

Exhibit 14: PRA method as a part of the CBA used in the SCORE tool.

The result of the case study shows that the alternative that handles the largest amounts of soil material also has the highest project risk cost. This is a result of the significant contribution of possible extra excavation and disposal given the uncertainty regarding the contamination level. This risk is also present for the other alternatives. On the other hand, for alternatives 2, 3 and 4 the amount of soil is not as large and the consequences linked to possible extra excavation and disposal is therefore not as high. Moreover, alternatives 3 and 4 have a more detailed design due to the extra steps in the remediation measure, i.e. sieving and soil-washing, which has a positive impact on the total risk cost. The result of the PRA shows which alternative has the lowest total project risk cost, and the PRA tool also ranks them accordingly. The PRA can also generate the probability of the different alternatives to be the alternative with the lowest risk cost. The alternative with the lowest total risk cost is regarded as being the best alternative given that the alternative does not have any unacceptable risks that need to be addressed. Unacceptable risks can derive from high probabilities, high consequences, and/or large interval of these, i.e. high uncertainty of input variables. To lower the level of uncertainty of input variables, the probabilities and consequences that contribute most to the uncertainty and the total risk cost need to be addressed in the iterative loop described in the PRA method.

The PRA method developed in this study has been prepared for evaluating remediation alternatives prior to construction. If used in publicly funded projects for example, it could be necessary to add project risk categories to capture the impact on the wider perspective of society, the environment and the economy. The PRA method could be one way of meeting the demand from the construction industry to manage uncertainties and avoiding costly unexpected events in construction projects by directing efforts to minimizing risks (Taroun, 2013). Using a PRA method such as the one described in this paper, i.e. a structured assessment, would result in a better-informed and prepared decision-maker, which would lead to more well-founded decisions and hopefully lower costs for unexpected events.

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Paper II

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Cost-benefit analysis as a part of sustainability assessment of remediation alternatives for contaminated land

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Abstract

There is an increasing demand among decision-makers and stakeholders for identifying sustainable remediation alternatives at contaminated sites, taking into account that remediation typically result in both positive and negative consequences. Multi-criteria analysis (MCA) is increasingly used for sustainability appraisal, and the Excel-based MCA tool Sustainable Choice Of REmediation (SCORE) has been developed to provide a relevant and transparent assessment of the sustainability of remediation alternatives relative to a reference alternative, considering key criteria in the economic, environmental and social sustainability domains, and taking uncertainty into explicit account through simulation. The focus of this paper is the use of cost-benefit analysis (CBA) as a part of SCORE for assessing the economic sustainability of remediation alternatives. An economic model is used for deriving a cost-benefit rule, which in turn motivates cost and benefit items in a CBA of remediation alternatives. The empirical part of the paper is a CBA application on remediation alternatives for the Hexion site, a former chemical industry area close to the city of Göteborg in SW Sweden. The impact of uncertainties in and correlations across benefit and cost items on CBA results is illustrated. For the Hexion site, the traditional excavation-and-disposal remediation alternative had the lowest expected net present value, which illustrates the importance of considering also other alternatives before deciding upon how a remediation should be carried out.

1. Introduction

Remediation of contaminated sites is primarily performed 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, society might benefit from new land use opportunities such as dwellings and recreation. At the same time, remedial actions are typically costly and associated with environmental impact such as emissions of carbon dioxide and other pollutants.

The contradictory effects of remediation have received increased attention among decision-makers and various stakeholder groups over the last decade, see e.g. Vegter et al. (2002) SuRF UK (2010), 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 Network for Industrially Contaminated Land in Europe (NICOLE) also suggests a framework for sustainability assessment (NICOLE and Common Forum, 2013). During 2004-2009 the Swedish EPA (2009a) 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 (ISO, 2014). The Sustainable Remediation Forum in the UK (SuRF UK, 2010) suggests a framework and indicators (criteria) for a sustainability evaluation of remedial actions, considering positive and negative environmental, economic and social effects. This ties the evaluation to the comprehensive “three-pillar” view on sustainability (UN, 2012), which also serves as the point of departure for this paper.

Sweden alone has 80 000 potentially contaminated sites (Swedish EPA, 2014). Similar, or worse, situations are reported from other countries. The large number of sites and the increased awareness and requirements regarding sustainability of remediation create a non-trivial situation for a decision-maker, in particular since there are usually several remediation alternatives available for carrying out a remediation project, and these alternatives might imply different consequences across actors in society. For example, the much applied excavation-and-disposal alternative removes contamination from the site, but usually requires a lot of transports and suitable conditions for taking care of the contaminated soil somewhere else. *In situ* techniques often introduce larger project risks as it is typically more difficult to design and control the effects of such measures compared to excavation and disposal. On-site *ex situ* techniques such as soil washing and soil sieving will create opportunities for reuse of material on site, but also risks with regard to dusting and noise. Another alternative that might sometimes be applicable is to leave the site as it is, with appropriate fencing and documentation of the contamination, but with a piece of land that might not be possible to use for any purpose. A decision-maker is thus likely to need advice on what remediation strategy is the most preferable one from a sustainability point of view.

Multi-criteria analysis (MCA) is increasingly used to provide support in environmental decision-making and for sustainability assessment (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 fulfills a set of performance criteria. MCA includes qualitative, quantitative and semi-quantitative methods and has been suggested for integrating economic, social and environmental sustainability into a comprehensive sustainability assessment of alternative remedial actions by a number of authors, e.g. Harbottle et al. (2008), Rosén et al. (2009), Linkov and Moberg (2011), and Brinkhoff (2011).

The Sustainable Choice Of REmediation (SCORE) tool is an Excel-based MCA tool developed to provide a relevant and transparent assessment of the sustainability of remediation alternatives relative to a reference alternative, considering key criteria in the economic, environmental and social sustainability domains, and taking uncertainty into explicit account through Monte Carlo simulation, see Rosén et al. (2014) for details. SCORE assesses economic sustainability of remediation alternatives through applying cost-benefit analysis (CBA) for evaluating their social profitability (for examples of such CBA applications in other contexts, see Paltrinieri et al., 2012; Perini and Rosasco, 2013; Rondon et al., 2010). CBA relies on welfare economics for expressing positive and negative consequences of alternatives in monetary units, i.e. in benefits and costs, see e.g. Johansson (1993) and de Rus (2010). This makes it possible to compute a sum of all benefits and costs; a positive (negative) sum means that the alternative entails a positive (negative) social profitability. While CBA have been applied earlier to remediation issues (some recent examples are Compernolle et al., 2013; Guerriero et al., 2011; Lemming et al., 2010; Mishra et al., 2012; Sparrevik et al., 2012; van Wezel et al., 2008), this paper contributes to the literature by giving a theoretical basis to cost and benefit items in the case of remediation alternatives, applying CBA with due considerations of uncertainties associated with those items, and applying it within an MCA and sustainability context.

This paper is organized as follows: Section 2 presents an economic model from which a cost-benefit rule is derived. This rule indicates in principle what types of costs and benefits should be included in a CBA of remediation alternatives. This is the basis for a more detailed identification of cost and benefit items in Section 3. Section 4 applies CBA to the case of the remediation of the Hexion site, a former chemical industry area close to the city of Göteborg (Gothenburg) in SW Sweden. The application allows an illustration of the impact of correlations and uncertainties associated with benefit and cost items on the results of a CBA. Section 5 is a concluding discussion, which relates CBA to the wider sustainability assessment through the MCA approach of SCORE.

2. A general equilibrium cost-benefit rule

While the selection of a remediation alternative could imply considerable consequences to some actors in society, we assume a remediation project that is small for the economy as a whole, i.e. it does not have a general impact on market prices. Further, we assume a small, open, and reasonably well-functioning market economy, i.e. prices tend to adjust continuously so as to clear markets. We thus adopt a general equilibrium setting for the CBA, following e.g. Johansson (1993), Johansson and Kriström (2012).

For deriving cost-benefit rules, assume a representative individual whose well-being can be described by the following indirect utility function:

$$V = V\left[p, w, y + \Pi(p, w, z) - \tau, z\right], \qquad \text{(Eq. 1)}$$

where V is indirect utility, p is a vector of prices for market goods, w is a vector of prices for inputs, y is income, Π is the sum of firms' profits, τ is a lump-sum tax collected by the government[1], and z is the non-market good of environmental quality. In the remediation setting, the amount of clean land could serve as a proxy for z. Increasing z through remediation involves costs due to the use of real resources such as labor and other inputs. dC denotes those costs, measured at the prices prevailing before the remediation is carried out.

From this setting, the following general equilibrium cost-benefit rule can be derived, see Johansson (1993):

$$\frac{dV}{V_y} = \left(x^s - x^d\right)dp + (L^s - L^d)dw + \left[pF_z dz + \left(\frac{V_z}{V_y}\right)dz - dC - dCV\right] = 0, \qquad \text{(Eq. 2)}$$

where $V_y = \partial V/\partial y$ is the individual's marginal utility of income, x denotes quantities of market goods, L is quantities of inputs, superscripts s and d denote supply and demand, $F_z = \partial F[L(z),z)]/\partial z$ is firms' marginal product of environmental quality, where F(•) is a production function, $V_z = \partial V/\partial z$ is the individual's marginal utility of environmental quality, and dCV is a payment (compensating variation) from the individual that would make her remain at her initial level of utility.

If markets are well-functioning, adjustment of prices would make demanded quantities of products and inputs equal to supplied quantities, i.e. $x^s = x^d$ and $L^s = L^d$. This general equilibrium feature implies that the two first terms are equal to zero. This means that a project resulting in an improvement of environmental quality dz is socially profitable if $dCV > 0$. That is, if:

$$pF_z dz + \left(\frac{V_z}{V_y}\right)dz - dC > 0, \qquad \text{(Eq. 3)}$$

where

1. $pF_z dz$ is the value to firms of the marginal product of environmental quality
2. $(V_z/V_y)dz$ is the individual's monetary valuation of the improved environmental quality
3. dC is the direct costs for carrying out the remediation, as explained above

These are thus the three main categories from which benefit and cost items of remediation can be identified. We study each of these categories in turn.

[1] This tax is collected for funding environmental projects. A lump-sum tax is the simplest possible case, and can be refined to a more realistic setting.

1. For explaining how $pF_z dz$ can be interpreted in practice, consider an example of a construction company whose production is dependent of clean land (z) as an input in its production of e.g. dwellings. The profits for such a firm are:

   $$\Pi = px(p,w,z) - w_m L_m(z) - wL(p,w) - K \qquad \text{(Eq. 4)}$$

   where p is the m^2 price of a dwelling, x is the total amount of dwellings sold in m^2, w_m is the m^2 price of land, L_m is the amount of land in m^2, w is the price of all other inputs, L is all other inputs, and K is fixed costs. Assume that L_m is the only input influenced by z, the m^2 of clean land. L_m is a function of z because an increase (decrease) in z implies that more (less) land can be used as an input in the production of dwellings. This firm's production function is $x = F[L_m(z),L]$, which means that the marginal product of environmental quality (F_z) is $dx/dz = \partial F(\bullet)/\partial z = \partial F/\partial L_m \times dL_m/dz$.

   Empirically, F_z is about how many more dwellings can be produced if there is a marginal increase in the amount of clean land. $pF_z dz$ is thus the market value of the extra dwellings that can be produced at the site thanks to the increase in the amount of clean land. We assume that the property market is well-functioning, making this market value to be reflected by property prices. This means that $pF_z dz$ is equal to the after-remediation increase in property value on site due to the increase in the amount of clean land. We identify this as benefit item B1, to be more discussed in Section 3.

2. The individual's monetary valuation $(V_z/V_y)dz$ is due to ways in which dz contributes to well-being. These are about benefits related to human health and ecosystem services (items B2 and B3 in Section 3), but also possibly other positive externalities caused by the remediation (item B4 in Section 3).
3. The direct costs dC for carrying out the remediation include what we refer to as remediation costs (cost item C1), see Section 3. However, the remedial action *per se* might, as was noted in Section 1, also result in externalities influencing health and ecosystem services negatively. These negative externalities are referred to as cost items C2 and C3 in Section 3. It might possibly also exist other negative externalities caused by the remedial action (item C4 in Section 3).

3. Benefit and cost items

Table 1 lists benefit and cost items based on the different categories identified from the cost-benefit rule in Section 2. Those items, and associated sub-items, are included in the SCORE tool and described in more detail below (see also Anderson et al., 2014).

3.1 Benefits

Increased property value on site (B1). An increase in property value because of the remediation can be interpreted as the property market's valuation of the flow of expected extra profits due to an increased capacity of the land to produce a flow of goods and services over time, e.g., allow the production of more dwellings. B1 is thus the difference between the property value *after* the remediation and the property value due to the flow of expected profits in the situation *before* remediation. Note that B1 is to be computed without influence of remediation costs on property values because these costs are accounted for separately in cost item C1, see below.

Improved health (B2), increased provision of ecosystem services (B3) and other positive externalities (B4). These other benefit items are all about positive externalities, i.e. they are about consequences which are not accounted for by the increased property value on site in B1. Reductions in health risks, either acute ones (B2a) such as poisoning, or non-acute ones (B2b) such as exposure to carcinogenic substances, are a possible consequence of remediation. A third sub-item (B2c) includes other types of improved health, i.e. the remediation might also contribute to increased well-being through for example mitigating anxiety caused by the contamination. Further, the remediation may result in a number of positive environmental effects having impact on human well-being, i.e. increasing the supply of ecosystem services in a broad sense (TEEB, 2010). Recreational opportunities are one ecosystem service often influenced positively by remediation. New or improved areas for recreation might be created on the remediated site (B3a) and/or in the surroundings to the site (B3b). B3c is a sub-item for increased provision of other ecosystem services, e.g. an improved capacity of water systems affected by the site to support agricultural activities. Finally, B4 is the item for other positive externalities than B2 and B3. Examples of B4 might include the creation of new knowledge by developing a new remediation technique, agglomeration economies that might be caused through the establishment of a new activity at the site, and an increase in cultural values through restoring industry buildings or other cultural heritage.

3.2 Costs

Remediation costs (C1). Based on e.g. USACE and USEPA (2000) and Rosén et al. (2008), the costs for carrying out the remediation are divided into the following cost sub-items:

- Design of remedial actions (C1a)). Costs associated with site investigations and design of remedial actions, including institutional controls. These costs are specific to the remedial design, in contrast to project management costs (C1b). Institutional controls are administrative and legal measures with the objective to reduce exposure to site contamination.
- Project management (C1b). Costs associated with project management, technical support, and working environment. These costs are *not* specific to remedial design.
- Capital costs (C1c). Costs referring to the interests paid on potential loans financing the remedial action and depreciation of human-made capital such as machines in case such depreciation is not reflected by the market price of using machines.
- Remedial action (C1d). Costs associated with mobilization, remediation work, and demobilization. Mobilization includes activities such as establishment of facilities and preparation of the site, i.e. preparation activities required for performing the remedial action.
- Monitoring programs (C1e). Costs associated with monitoring are of three types; (1) monitoring during the remedial action, (2) monitoring with the objective to terminate the remediation, and (3) post-action monitoring.

- Project risks (C1f). While some events with an uncertain outcome might have been prevented through, for example, site investigations and project management, some probabilistic costs are likely to remain. Such project risks might be associated with the remediation method (e.g. the remedial design turns out to be inappropriate or inefficient), authorities (e.g. remediation permits are delayed), public opinion (e.g. extra information about the remediation turns out to be necessary to communicate), project organization and financial structure (e.g. the project organization has communication problems that could affect the efficiency of the remediation measure), technical basis for assessment (e.g. the volume of the contaminant is found to be underestimated), and liability issues (e.g. the contaminant unexpectedly affects an adjacent lot) (Brinkhoff et al., 2014).

The remedial action *per se* may result in a number of negative externalities, i.e. costs not incurred by the party responsible for the remediation and therefore not accounted for in C1. They are grouped into the cost items of *impaired health due to remedial action* (C2), *decreased provision of ecosystem services due to remedial action* (C3), and *other negative externalities* (C4). Item C2 is further divided into increased health risks due to remedial action on site (C2a), transports to and from the site (C2b), and at disposal sites (C2c) where the contaminated material are placed temporarily or permanently. Such increased health risks could be caused by, e.g., noise and emissions, and heavy transports that imply a reduced traffic safety. Other types of impaired health due to remedial action (C2d) are also possible. For example, public distrust in the chosen remediation technique might cause worry that contaminants are spreading rather than being properly handled. Similar sub-items are found for C3, i.e. decreased provision of ecosystem services on site (C3a), outside the site (C3b), and at the disposal site (C3c) through, for example, emissions caused by remediation work and transports. Finally, item C4 includes other negative externalities than C2 and C3. A common example is the reduction of cultural values through impairment or destruction of cultural heritage at the site.

Table 1. Benefit (B) and cost (C) items due to a remediation alternative.

Main items	Sub-items
B1. Increased property value on site	
B2. Improved health	B2a. Reduced acute health risks
	B2b. Reduced non-acute health risks
	B2c. Other types of improved health, e.g. reduced anxiety
B3. Increased provision of ecosystem services	B3a. Increased recreational opportunities on site
	B3b. Increased recreational opportunities in the surroundings
	B3c. Increased provision of other ecosystem services
B4. Other positive externalities than B2 and B3	
C1. Remediation costs	C1a. Design of remedial actions
	C1b. Project management
	C1c. Capital costs
	C1d. Remedial action
	C1e. Monitoring
	C1f. Project risks
C2. Impaired health due to remedial action	C2a. Increased health risks on site
	C2b. Increased health risks from transports activities
	C2c. Increased health risks at disposal sites
	C2d. Other types of impaired health, e.g. increased anxiety
C3. Decreased provision of ecosystem services due to remedial action	C3a. Decreased provision of ecosystem services on site
	C3b. Decreased provision of ecosystem services in the surroundings
	C3c. Decreased provision of ecosystem services at disposal sites
C4. Other negative externalities than C2 and C3	

3.3 Net present value

In a deterministic setting, Eq. (3) is empirically evaluated by computing the net present value (*NPV*) of a remediation alternative:

$$NPV = \sum_{t=0}^{T} \frac{1}{(1+r_t)^t}(B_t - C_t), \qquad \text{(Eq. 5)}$$

where $B_t = B1_t + B2_t + B3_t + B4_t$ and $C_t = C1_t + C2_t + C3_t + C4_t$, i.e. the sum of benefits and costs at time t (usually years), r_t is the social discount rate at t, and T is the time horizon associated with the benefits and costs. The remediation alternative associated with the highest *NPV* is the most profitable one to society (or, if $NPV<0$, the one that gives the least social loss).

In principle, SCORE applies an equivalent but often more practical way to compute *NPV*. The present value (*PV*) of each benefit and cost item i is computed as:

$$PV(B_i) = \sum_{t=0}^{T} \frac{1}{(1+r_t)^t} B_{it} \text{ and } PV(C_i) = \sum_{t=0}^{T} \frac{1}{(1+r_t)^t} C_{it}. \quad \text{(Eq. 6)}$$

and then *NPV* is calculated as:

$$NPV = \sum_{i=1}^{4} PV(B_i) - \sum_{i=1}^{4} PV(C_i), \quad \text{(Eq. 7)}$$

However, as explained in the next sub-section, SCORE applies this in a probabilistic setting because of uncertainties associated with costs and benefits.

3.4 Uncertainty and correlations

Quantifications of benefits and costs will always be associated with some uncertainty, i.e. the effects of the remedial alternatives can never be assessed 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, CBA involves human subjectivity through considerations made by the cost-benefit analyst such as choices of data sources. A certain degree of subjectivity is unavoidable (Harbottle et al., 2008).

The treatment of uncertainty in SCORE follows a Monte Carlo simulation approach, where lognormal distributions are applied for representing uncertainties in the cost and benefit items listed above. A user of SCORE is supposed to (1) provide the most likely value (*MLV*) of the present value (*PV)* of each of the cost and benefit items and (2) to assign its uncertainty level by choosing one of three different levels of uncertainty: high, medium or low, corresponding to the error factors of $\sqrt{10} \approx 3.16$, 2 and 1.25, respectively. Note that the UCL (Upper Credibility Limit or largest reasonable *PV*) equals $m\varepsilon$, where m denotes the median and ε the error factor, while the LCL (Lower Credibility Limit or lowest reasonable *PV*) equals m/ε (Rausand and Høyland, 2004). Thus, the ratios $\frac{UCL}{LCL} = \varepsilon^2$ are 10, 4 and 1.5625 for the three levels of uncertainty. Denote by μ and σ the mean and standard deviation on the log scale of the uncertainty distribution for PV. Then $\sigma = (\log \varepsilon)/z_\alpha$ and $\mu = \log MLV + \sigma^2$, where z_α denotes the standard normal quantile corresponding to the risk α. This follows readily from well-known properties of the lognormal distribution. Our final choice is to let $\alpha = 0.05$. Thus the credibility (or certainty) of the interval between LCL and UCL is 90 %. Table 2 illustrates the relative size of this interval for the high, medium and low level of uncertainty, and Figure 1 shows the lognormal uncertainty distributions for PV for the three levels of uncertainties given *MLV*=1.

Table 2. The relative size of the 90 % credibility interval for the three standard uncertainty levels of cost and benefit items. For example, the credibility interval ranges from 0.60MLV to 2.39MLV for medium uncertainty.

Uncertainty category	**LCL/MLV**	**UCL/MLV**
High	0.52	5.16
Medium	0.60	2.39
Low	0.81	1.27

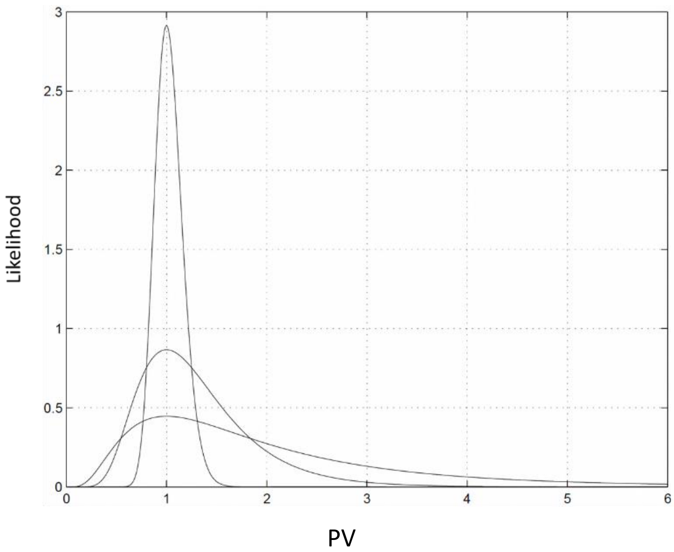

Figure 1. Log-normal uncertainty distributions for three levels of uncertainty and MLV=1.

In addition to uncertainties, dependencies between benefit and/or cost items might have a considerable impact on the results of a Monte Carlo simulation. Dependencies between lognormal distributions are easily modelled by the covariance matrix for the logarithmic variables. Let A and B be two cost or benefit items, and let R_i, for i=1,2, be two variables that influence A and B. Assume that the R_i's are independent normal and write ρ_{Xi} for the correlation between $\log X$, where $X = A, B$, and R_i.

The correlation between $\log A$ and $\log B$ can then be shown to equal

$$\rho_{AB} = \rho_{A1}\rho_{B1} + \rho_{A2}\rho_{B2} \qquad \text{(Eq. 8)}$$

provided the remaining randomness in A and B is independent, i.e. A and B are conditionally independent given R_1 and R_2, and, for $X = A, B$,

$$\rho_{X1}^2 + \rho_{X2}^2 < 1 \qquad \text{(Eq. 9)}$$

This result can easily be extended to more than two items and variables. It is proved by well-known properties of the multivariate normal distribution.

Depending on whether the cost or benefit items A and B are of the same type or not, their sum $S = A + B$ or difference $D = A - B$ is of interest in an *NPV* calculation. In order to understand how the correlation affects their sum/difference, note that

$$\mathrm{Var}(S) = \mathrm{Var}(A) + \mathrm{Var}(B) + 2\mathrm{Cov}(A, B) \qquad \text{(Eq. 10)}$$

and

$$\mathrm{Var}(D) = \mathrm{Var}(A) + \mathrm{Var}(B) - 2\mathrm{Cov}(A, B) \qquad \text{(Eq. 11)}$$

where $\mathrm{Cov}(A, B) = \rho\sqrt{\mathrm{Var}(A)\,\mathrm{Var}(B)}$, and ρ is the correlation between items A and B. Note that ρ and ρ_{AB} are different, since the latter is defined on the log scale. For instance, if two strongly positively dependent items are of approximately the same size and is provided with the same uncertainty (high, medium or low), then Eq. 10. (Eq. 11) suggests that the uncertainty in their sum (difference) might be considerably larger (smaller) than what would be expected in case of independent uncertainties. In the case of strong negative dependence, these effects would be reversed. It may also be seen from Eq. 10-11 that even a strong correlation does not considerably affect the uncertainty in the sum/difference if the *MLV* of one item is much larger than the other. This is due to the fact that the credibility interval is wider for items with a larger *MLV*.

4. An application

A CBA of remediation alternatives is applied as a part of the SCORE tool to the remediation of the Hexion site, introduced in subsection 4.1. The CBA followed the six-step procedure below and is summarized in subsection 4.2, followed by an analysis in subsection 4.3 of the potential impact of uncertainty and correlation across benefit and/or cost items.

1. Identification of remediation alternatives, a reference alternative and a time horizon associated with the alternatives.
2. Identification of costs and benefits, followed by qualitative valuation of the importance of each cost and benefit item.
3. Quantification and monetization of costs and benefits, including a choice of social discount rate. The results are inserted in the SCORE tool as the *MLV* of the *PV* of each benefit and cost item, see Section 3.4. Quantification and monetization is typically a demanding task, requiring a substantial amount of data. The qualitative evaluation in step 2 is therefore used for prioritizing what items should be quantified and monetized. If quantification and monetization are not feasible within reasonable effort for some costs and benefits, the qualitative valuation from step 2 is maintained.
4. Specification of uncertainty of each present value, see Section 3.4.

5. Simulation of *NPV* (see Section 3.4) through the SCORE tool[2] and concluding about overall profitability by taking into account the qualitative valuation from step 2 and the results of the uncertainty analysis.
6. Distributional analysis, in which the *NPV* for different actors is studied.

4.1 The site

The Hexion site is a 35 000 m^2 property located approximately 800 m east of the center of Mölndal, a municipality adjacent to the city of Göteborg in SW Sweden. The area in which the Hexion site is located has a long history of industrial activity because of the vicinity to the river Mölndalsån. Former operations on the Hexion property were for about 180 years chemical industries of various kinds. In 2007, the construction company NCC AB acquired the property with the purpose of developing the property into a residential area of metropolitan character, including office/commercial premises, a pre-school, green space including playgrounds, and parking areas.

The site has a dramatic topography with large elevation changes and a complex geology because the Göteborg moraine runs through the property, composed of till and fluvial material with some elements of clay. The site has been partially filled with varying thickness (0-5 m). Natural materials, mainly silty sand and sandy silt, is found underneath the filling material. Soil investigations showed that large areas were unaffected or affected to a small extent by past activities (Magnusson and Norin, 2007). Contaminants are mainly found superficial (0-1 m) but in limited areas at greater depths (4-8 m). Different sub-areas were identified and could be traced to the various activities by the previous operations, e.g. depositing, filling containers or storage of chemicals, i.e. source areas. The contaminants in these areas consisted primarily of phthalates, lead and solvents. Investigations of groundwater showed contaminants in the source areas but no spread could be detected from these. However, a slight spread of contaminants from under the buildings was detected. A site-specific risk assessment indicated a need for a remediation that would reduce risks to human health as well as risks to the water recipient (the river Mölndalsån) and to soil ecosystems. The risks were mainly associated with the topsoil and the deep soil in smaller restricted areas.

Three overall remediation goals were established: (1) after the remediation the site should be fit for the planned residential area, (2) conditions for the ecological systems (vegetation and soil fauna) in the superficial layers should be enhanced and the remediation should aim at protecting human health and the water recipient of the river Mölndalsån, and (3) long-term water quality in the river Mölndalsån should be secured. Any contribution of pollutants from the Hexion site should be minimized. Further, quantifiable remedial objectives were formulated for the substances/compounds that occurred most frequently at levels higher than those of the Swedish EPA's generic guidelines values for sensitive land use. These substances and compounds were: Lead, barium, PAHs, aliphatic and aromatic hydrocarbons, ethyl benzene, xylene and the phthalate DEHP. Different quantifiable remedial objectives were applied to surface soil and more deeply located soil.

[2] The Excel add-in of Oracle Crystal Ball is used for the simulations in SCORE.

Four remediation alternatives were identified, 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:

1. Excavation and disposal of all soil with a contamination level exceeding the generic guideline values for "sensitive land use" according to Swedish EPA (2009b). These limits are applied for all depths of the ground. The soil is excavated and transported to a landfill. No further treatment of the excavated soil is performed.
2. As alternative 1 but based on site-specific guideline values, with lead and DEHP as the design pollutants. Those values are based on a site-specific risk assessment, taking into consideration the expected exposure conditions and environmental protection values at the site (Sweco, 2009).
3. As alternative 2, but the contaminated soil is sieved on site. Parts of the material can be used for refilling at the site and the material not suitable for refilling is transported to a landfill.
4. As alternative 3, but with soil washing on-site as an additional treatment, which will increase the amount of soil possible to use for refilling, thus further decreasing the need for transports to landfills.

Moreover, alternatives 3 and 4 included secondary analysis for classification of the pretreated soil for transportation to a suitable disposal site. The reference alternative is defined as a situation where the site, including the disused chemical factory, is fenced off and abandoned without remediation.

More details about the Hexion site are found in Landström and Östlund (2011) (henceforth L&Ö). The results presented below rely to a great extent on their data.

4.2. Summary of the CBA

Cost and benefit items of each remediation alternative were identified and qualitatively valued by using the following scale: "X" for items judged to be very important, "(X)" for somewhat important, and "NR" for not relevant or not important for the Hexion site. Quantification and monetization efforts then focused on the items judged to be very important, see the list below, which also summarizes how they were monetized (see L&Ö for details, if not otherwise stated). Table 3 shows the qualitative values and MLVs of PVs for each of the monetized items in the way in which they are entered into SCORE. In a base case, the social discount rate of 3.5 % recommended for CBA in Sweden was applied (STA, 2012).

- Increased property value on site (B1) thanks to the development on the site that can be realized. Monetization was based on an interview with a representative of the construction company developing the site.
- Reduced non-acute health risks (B2b) thanks to decreased concentration of DEHP and PAH-H in soil. Estimates of reduced on-site cancer risk and mortality associated with cancer was used for the monetization together with the monetary value of a statistical life (VSL) recommended for Swedish CBA (Bångman, 2010; STA, 2012).

- Other types of improved health (B2c) because of reduced anxiety thanks to the remediation. The monetary value was approximated from a hedonic approach, where a likely increase in the market value of properties adjacent to the site was estimated and attributed to reduced anxiety about off-site health risks after the remediation.
- Increased recreational opportunities on site (B3a) thanks to improved public accessibility to the site because of the remediation. The opportunity to use new green areas is likely to influence wellbeing in the neighborhood positively, but data for monetizing this item were not available.
- All sub-items of remediation costs (C1a-C1f) because of the considerable scale of the remediation project. Some of these costs differ across the remediation alternatives because of the reduced need for transports and excavation in alternatives 2-4 in comparison to alternative 1, and because of the additional treatment of sieving in alternatives 3 and 4, and soil washing in alternative 4. Data used by L&Ö did not allow costs for investigation and design of remedial action (C1a) and project management (C1b) to be sorted out from costs for the remedial action (C1d). Hence, the input value of C1d for SCORE in Table 3 includes C1a and C1b. Project risks (C1f) were subject to a separate in-depth analysis by Brinkhoff et al. (2014).
- Increased health risks due to remedial action on site (C2a) because of the cancer risks implied by exposure of workers to DEHP, PAH-H and lead during the remediation, and also the risk of on-site accidents during the remediation work. Again, VSL was applied for the monetization, and also a monetary value of an injury recommended for Swedish CBA (STA, 2012).
- Increased health risks due to transports to and from the site (C2b) because of the increased risks of traffic accidents implied by heavy vehicles transporting contaminated soil and refilling material. Risks were computed from data on the average number of accidents per transport km for various types of routes to be used for transports to and from the site, and the length and number of transports associated with each remediation alternative. The expected annual number of injuries was subsequently monetized by applying a recommended monetary value of an injury, cf. C2a.
- Decreased provision of ecosystem services outside the site due to the remedial action (C3b), primarily because of air emissions caused by the remediation activities on site and transports to and from the site. Available data allowed computation of CO_2 equivalents emissions from remediation work on site and transports to and from the site (Almqvist et al., 2011), which were monetized through a default cost of CO2 emissions suggested by STA (2012).

Table 3. CBA base case of Hexion remediation alternatives. All monetary values in million Swedish kronor (MSEK). P = Payer; B = Beneficiary; DEV = Developer; EMP = Employees; PUB = Public, including neighbors; MLV = most likely value of the present value; (X) = Non-monetized item judged to be somewhat important; X = Non-monetized item judged to be very important; NR = Non-monetized item judged to be of no relevance or no importance; Unc = degree of uncertainty; L = Low uncertainty; M = Medium uncertainty; H = High uncertainty.

Main items	Sub-items	Alternative 1			Alternative 2			Alternative 3			Alternative 4		
		B/P	MLV	Unc	B/P	MLV	Unc	B/P	MLV	Unc	B/P	MLV	Unc
B1. Increased property values		DEV	48.81	M	DEV	48.81	M	DEV	48.81	M	DEV	48.81	M
B2. Improved health	B2a		NR			NR			NR			NR	
	B2b	EMP	0.0003	M	EMP	0.0003	M	EMP	0.0003		EMP	0.0003	M
	B2c	PUB	0.07	M	PUB	0.07	M	PUB	0.07	M	PUB	0.07	M
B3. Increased provision of ecosystem services	B3a	PUB	X		PUB	X		PUB	X		PUB	X	
	B3b	PUB	(X)		PUB	(X)		PUB	(X)		PUB	(X)	
	B3c	PUB	(X)		PUB	(X)		PUB	(X)		PUB	(X)	
B4. Other positive externalities than B2 and B3			NR			NR			NR			NR	
C1. Remediation costs	C1a		NR			NR			NR			NR	
	C1b		NR			NR			NR			NR	
	C1c	DEV	1.18	M	DEV	0.78	M	DEV	0.77	M	DEV	0.95	M
	C1d	DEV	38.90	M	DEV	25.87	M	DEV	25.52	M	DEV	31.40	M
	C1e	DEV	9.32	M	DEV	9.32	M	DEV	9.32	M	DEV	9.32	M
	C1f	DEV	4.56	M	DEV	2.41	L	DEV	1.70	L	DEV	1.65	M
C2. Impaired health due to the remedial action	C2a	DEV	0.84	M	DEV	0.84	M	DEV	0.84	M	DEV	0.84	M
	C2b	DEV	1.52	M	DEV	0.90	M	DEV	0.77	M	DEV	0.64	M
	C2c		NR			NR			NR			NR	
	C2d	PUB	(X)		PUB	(X)		PUB	(X)		PUB	(X)	
C3. Decreased provision of ecosystem services due to remedial action	C3a	PUB	(X)		PUB	(X)		PUB	(X)		PUB	(X)	
	C3b	PUB	0.56	M	PUB	0.35	M	PUB	0.33	M	PUB	0.31	M
	C3c	PUB	(X)		PUB	(X)		PUB	(X)		PUB	(X)	
C4. Other negative externalities than C2 and C3			NR			NR			NR			NR	

As shown by Table 3, a medium degree of uncertainty was in the base case assigned to all items except for project risks (C1f). The in-depth analysis by Brinkhoff et al. (2014) shows, after Monte Carlo simulation, a less variable result in the distribution of risk cost for alternatives 2 and 3, hence a low uncertainty for these alternatives is chosen for the base case. The effects of changing the degree of uncertainty are studied in Section 4.3. As a rough basis for a distributional analysis, SCORE also allows entering codes for each item which groups enjoy (incur) most of the benefits (costs). In Table 3, three groups were identified: the developer, employees and the general public (including neighbors).

Figure 2 shows the simulation results for *NPV* for the four alternatives. While there is a substantial probability for a negative *NPV* for all four alternatives, expected *NPV* is negative only for the first alternative (MSEK -10.29). Figure 3 provides more details about the distribution of *NPV* for the case of the extensive excavation alternative 1 and show that a 90 % credibility interval for *NPV* is [-67.57,50.96]; the probability of a positive *NPV* for this alternative is about 0.35. Alternative 3 accounts for the highest expected *NPV* (MSEK 12.93), which suggests that there are economic reasons for sieving contaminated soil. Similarities across alternatives with respect to the non-monetized but very important item of improved recreational opportunities (B3a) suggest no change in the *NPV* ranking of alternatives if B3a is taken into account. A distributional analysis indicate that the *NPV* ranking also applies for the developer, whereas alternative 4 might be preferred by the public (see C3b in Table 3).

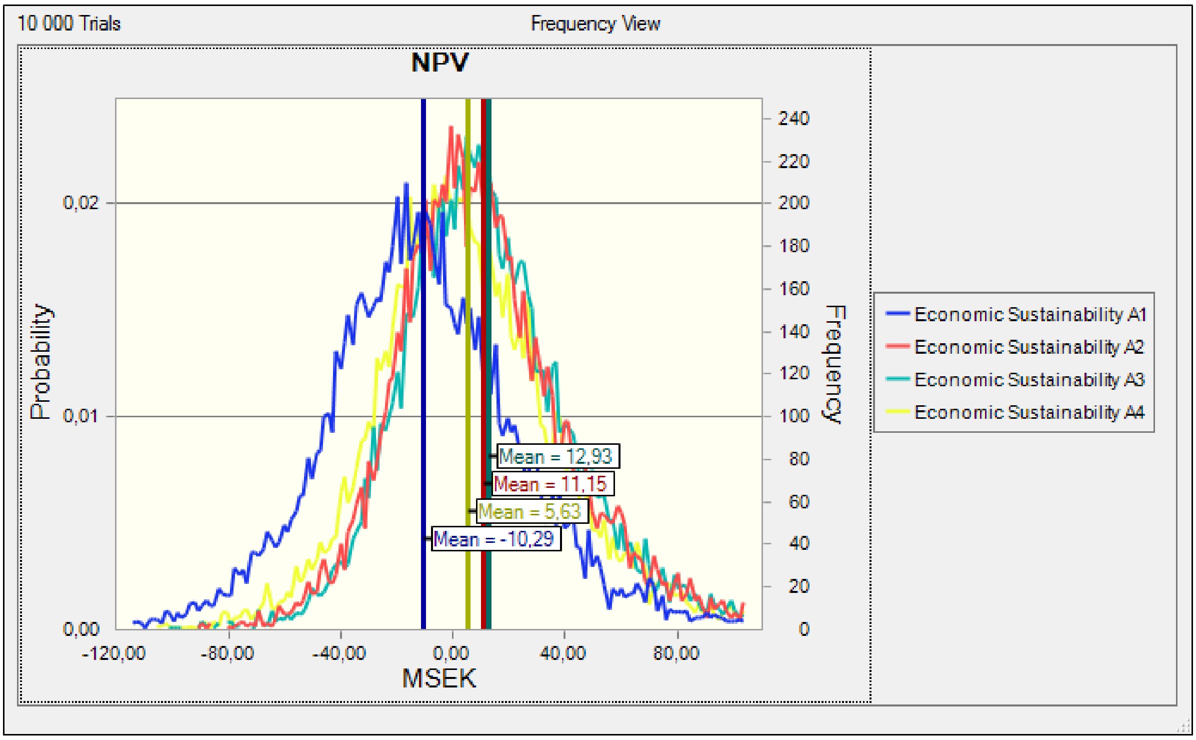

Figure 2. Simulation results (base case) for NPV for the four remediation alternatives.

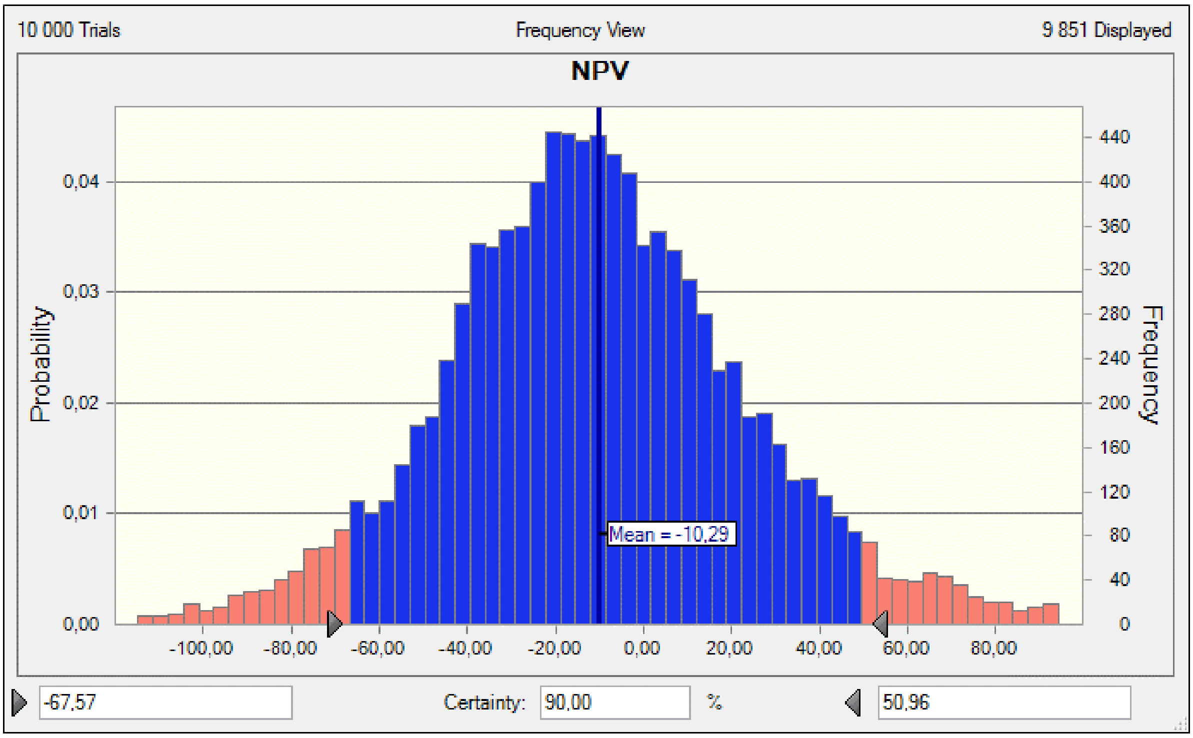

Figure 3. Simulation results (base case) for the probability distribution for NPV for alternative 1.

4.3 Analysis of the impact of uncertainty and correlations

4.3.1 Uncertainties

The considerable size of the property value item B1 in the Hexion case suggests that uncertainties in B1 might influence *NPV* results substantially. We therefore illustrate the capacity of SCORE to show the impact of the uncertainty specified for B1 on *NPV*, with a focus on the results for alternative 1. The qualitative implications of the analysis are similar for the other three alternatives.

Figures 4 and 5 shows the distribution of *NPV* in the cases when low and high uncertainty, respectively, is specified for B1 in SCORE. This can be compared to the results for the base case in Figure 3, in which medium uncertainty for B1 was assumed. As expected, Figure 4 shows that the 90 % credibility interval for *NPV* becomes less wide in the case when low uncertainty is assumed for B1: [-68.90,8.24] instead of [-67.57,50.96]. Another effect of assuming a low uncertainty for B1 instead of medium uncertainty is that the expected *NPV* is reduced from MSEK -10.29 to -24.11. This is because a lower uncertainty implies a lower probability for high positive values of B1. In the case of high uncertainty for B1, the probability of high positive values of B1 is increased, which results in an expected *NPV* amounting to MSEK 27.53 but also a considerably wider credibility interval for NPV: [-63.20,181.68], see Figure 5.

These results illustrate a considerable sensitivity of the selected uncertainty of B1 on expected WTP. This is not a surprising result considering the substantial size of the B1 item in relation to most other items, and it also illustrates the impact of how the uncertainty levels of cost and benefit items are defined in SCORE.

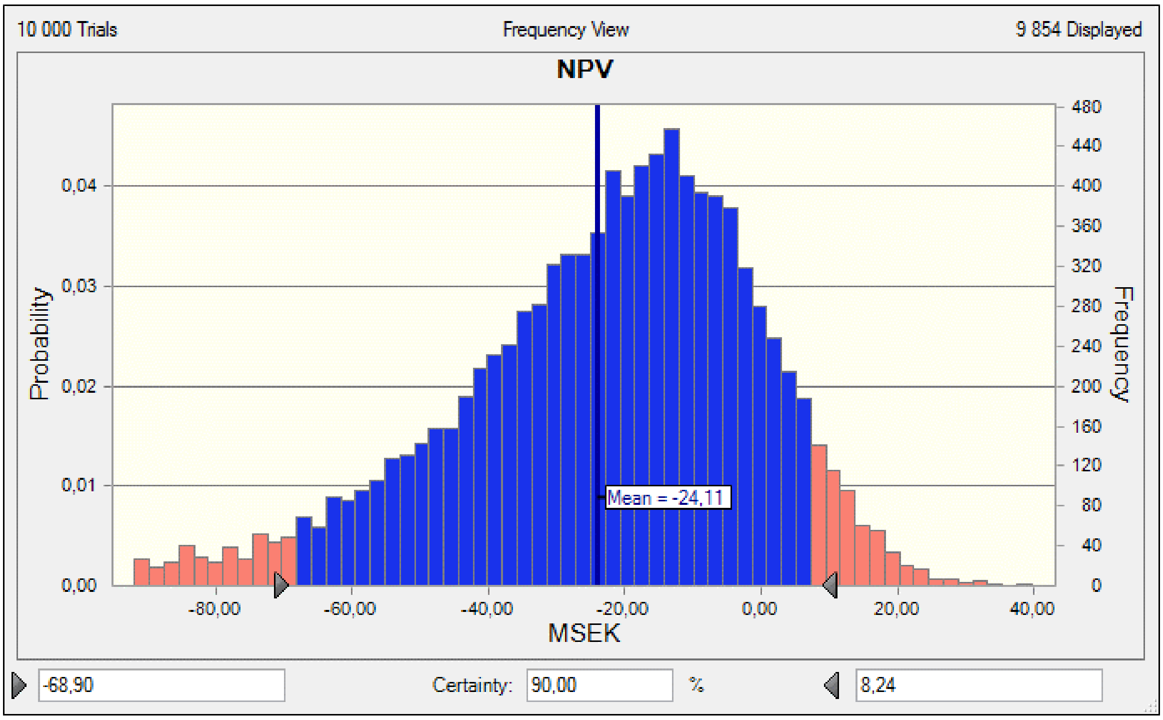

*Figure 4. Simulation results for the probability distribution for NPV for alternative 1 when **low** uncertainty is specified for benefit item B1.*

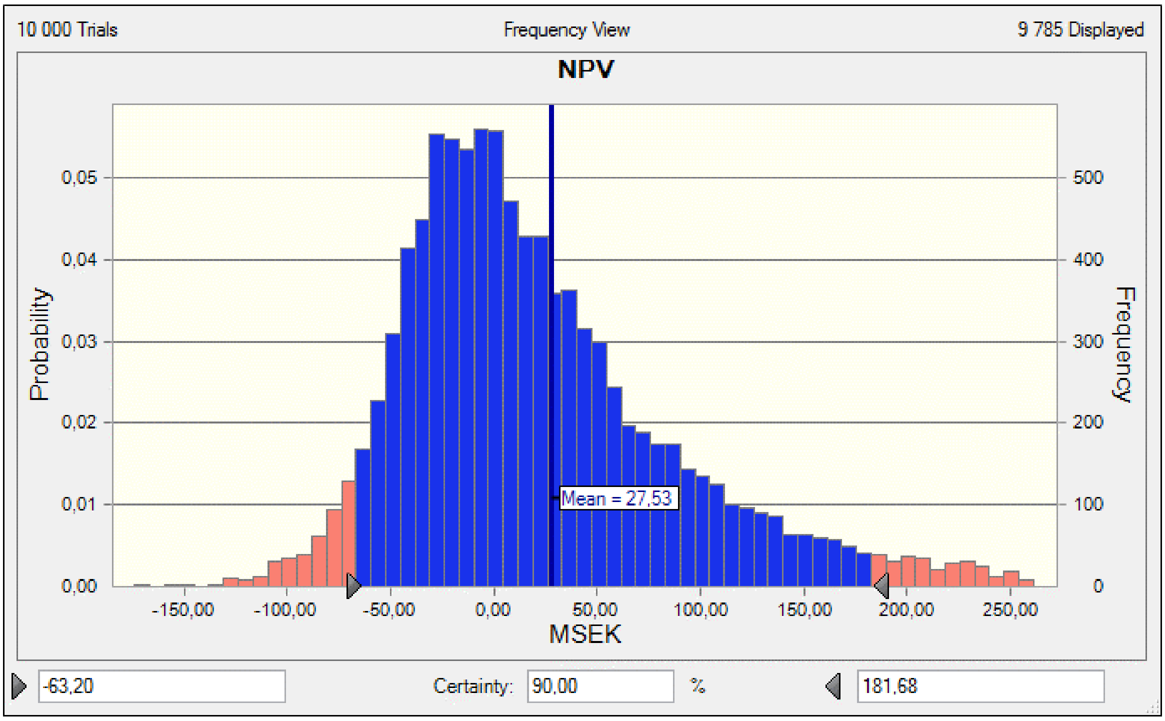

*Figure 5. Simulation results for the probability distribution for NPV for alternative 1 when **high** uncertainty is specified for benefit item B1.*

4.3.2 Correlations

We proceed by illustrating the consequences of potential dependencies between cost and/or benefit items, cf. Section 3.4. More precisely, we consider the consequence of positive and negative correlation, respectively, on the *sum* of items and the *difference* between items. In a CBA perspective, the sum could be about total costs or total benefits, and the difference could be about benefits minus costs, i.e. net benefits. We stick to the assumption of lognormal distributions of items throughout.

The case of the consequence of positive correlation on the sum of items applies readily to the Hexion case. This is because both the costs for the remedial action (C1d) and health risks due to transports to and from the remediation site (C2b) are dependent on the amount of transports and are thus positively correlated to each other. Alternative 1 is again used for the illustration, i.e. C1d = MSEK 38.90 with medium uncertainty (5 %: 23.34, 95 %: 92.97) and C2b = MSEK 1.52 with medium uncertainty (5 %: 0.91, 95 %: 3.63).

Figure 6 shows simulation results for the distribution of the sum of C1d+C2b when no correlation is assumed (red) and when a correlation coefficient of 0.9 is assumed (blue). As can be expected from Eq. 10, the presence of a positive correlation tends to create a wider credibility interval for the sum. However, this effect is small despite the substantial positive correlation, which is explained by the fact that C1d and C2b are not very equal in size, which causes the covariance term in Eq. 10 to be small. Figure 7 shows that the widening of the credibility interval for the sum as an effect of a positive correlation becomes considerably more pronounced if it is assumed that both C1d and C2b takes the value of MSEK 38.90, again with medium uncertainty.

Figure 8 is based on the same assumptions as Figure 7, but now the consequences of a strong positive correlation on the *difference* of C1d-C2b are studied instead. As can be expected from Eq. 11, the positive correlation now results in a less wide credibility interval for the difference. If *negative* correlation is assumed instead, the effects on the distribution of the sum and the difference are reversed in comparison to those illustrated for positive correlation.

The effects are summarized in Table 4 and suggests that dependencies between variables should be taken into account if the probability of exceeding (or not exceeding) a particular value for a sum or a difference is of importance. In a CBA characterized by a positive (negative) correlation between benefits and costs, one would expect a less wide (wider) credibility interval for the difference between benefits and costs (i.e. the net benefits) in comparison to a case when correlation is not taken into account. However, in the Hexion case, benefits are constant across alternatives while costs vary, which illustrates that benefits and costs are not necessarily correlated. It could also be of interest in a CBA to study the probability that the sum of benefits (costs) are greater (lower) than a particular value, which again suggests the relevance of the results in Table 4 in case of correlations across items.

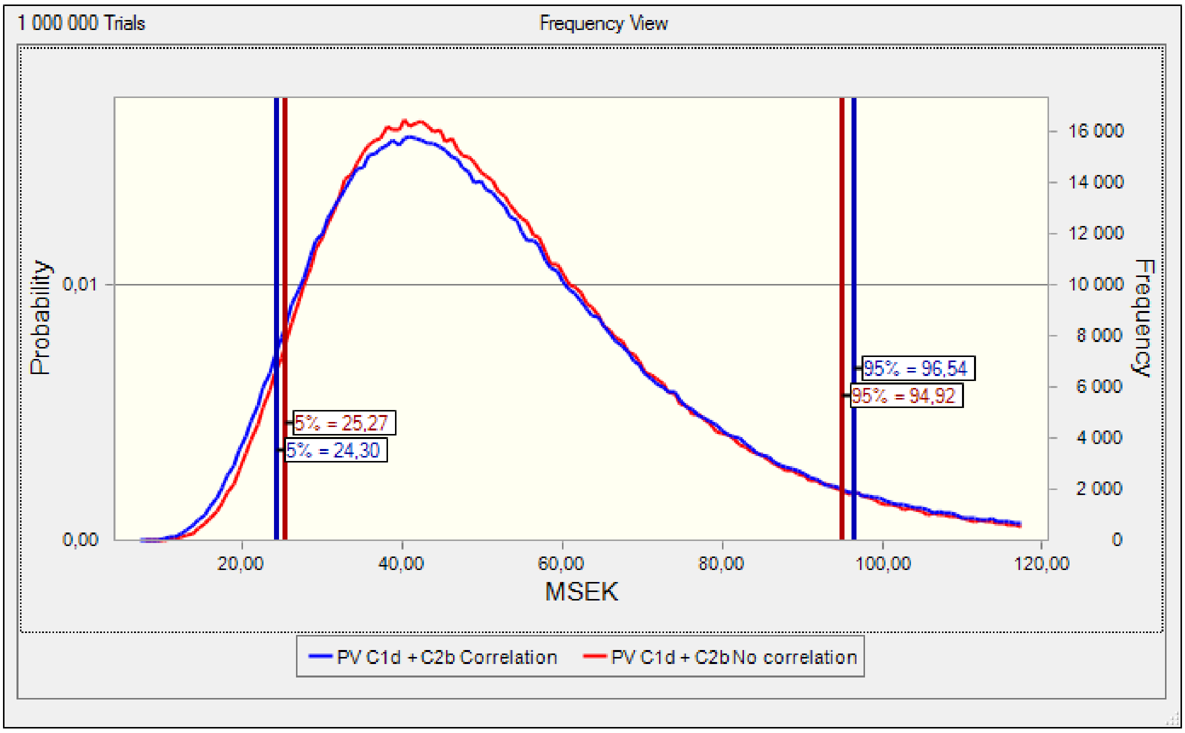

Figure 6. Simulation results for the distribution of the sum of C1d+C2b, where C1d = SEK 38.90 million and C2b = SEK 1.52 million. Red: No correlation between C1d and C2b is assumed. Blue: A correlation coefficient of 0.9 between C1d and C2b is assumed.

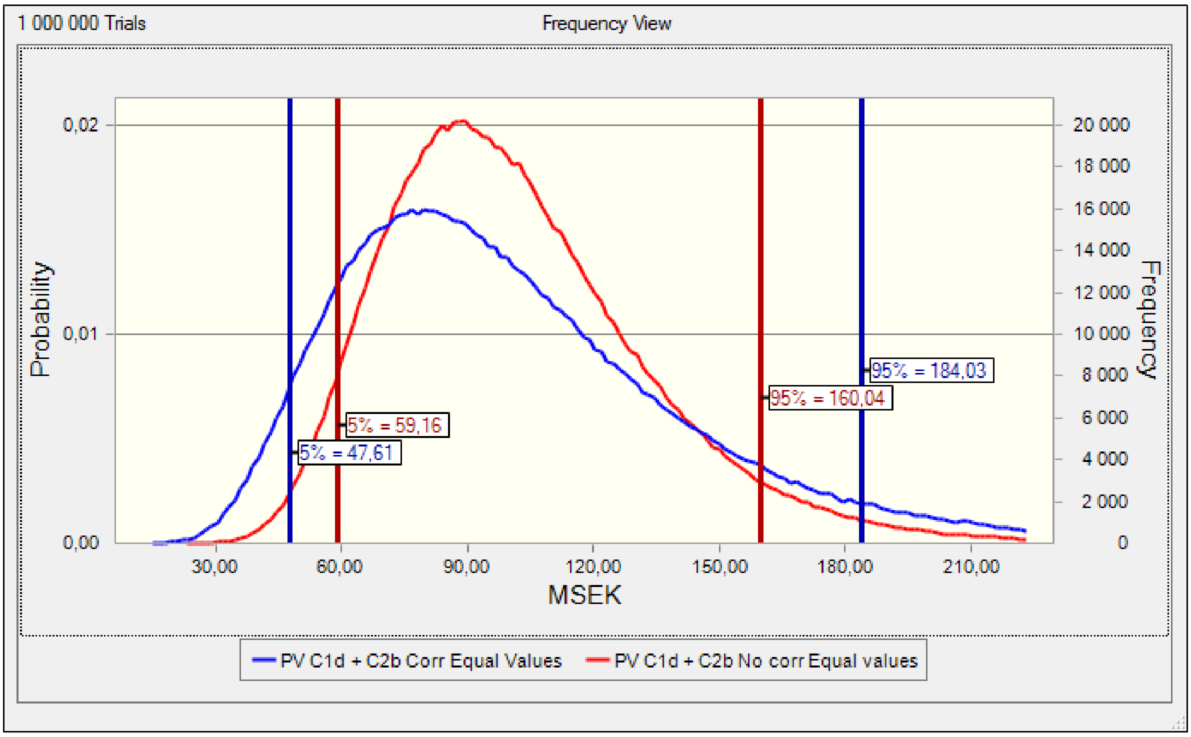

Figure 7. Simulation results for the distribution of the sum of C1d+C2b, where C1d = SEK 38.90 million = C2b. Red: No correlation between C1d and C2b is assumed. Blue: A correlation coefficient of 0.9 between C1d and C2b is assumed.

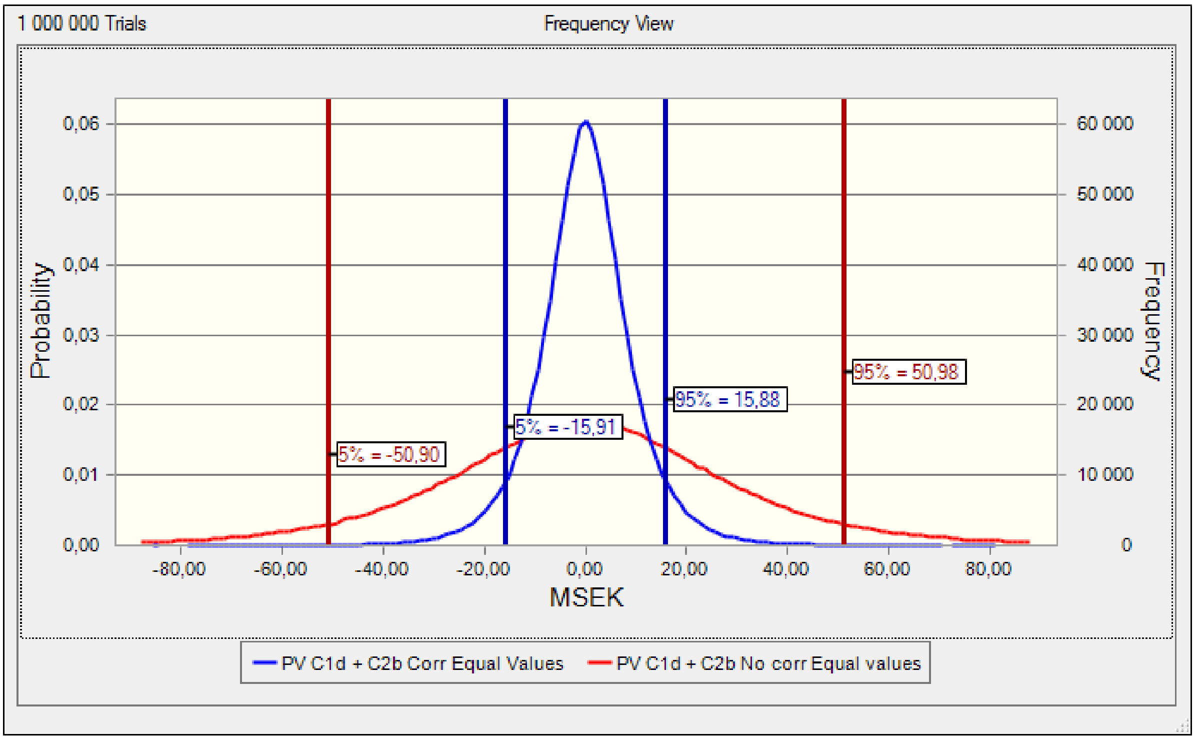

Figure 8. Simulation results for the distribution of the difference of C1d-C2b, where C1d = 38.90 million = C2b. Red: No correlation between C1d and C2b is assumed. Blue: A correlation coefficient of 0.9 between C1d and C2b is assumed.

Table 4. The general consequences of the presence of correlations on the sum and difference of costs or benefits items, in comparison to a case with no correlation.

	Positive correlation between items	**Negative correlation between items**
The sum of items	*Wider* credibility interval for the sum	*Less wide* credibility interval for the sum
The difference of items	*Less wide* credibility interval for the difference	*Wider* credibility interval for the difference

4.3.3 Choice of discount rate

CBA results might be very sensitive to the choice of the social discount rate, especially in applications with long time horizons. This has made the choice of social discount rate to a controversial issue, see Arrow et al. (2014) for a recent review. This issue is of considerable relevance also in a remediation context, because a remediation might cause, for example, long-term reductions of health risks and improved recreational opportunities. A SCORE user is supposed to choose a suitable rate or rates before making simulations, because MLVs of present values of benefits and costs are to be entered as input to the simulation. Therefore a level of uncertainty of the size of the discount rate(s) cannot be selected within SCORE. We illustrate instead the impact of the choice of discount rate on *NPV* by comparing the cases of a zero discount rate and a discount rate of 7 % with the base case of 3.5 %. 7 % is the social discount rate recommended in the United States for CBAs of intergenerational projects (OMB, 2003).

Figures 2, 9 and 10 show that a higher discount rate reduces the profitability of all four alternatives. This effect occurs mainly because the increase in property value (B1) is assumed to be realized after the costs of the remediation alternatives are incurred. The only item with a very long time perspective in the Hexion case is the reduction of non-acute health risks (B2b), which was assumed to be present in 350 years. The size of the discount rate indeed influences the size of B2b substantially: 0 %: MSEK 0.0041, 3.5 %: MSEK 0.0003, 7 %: MSEK 0.0001. However, B2b is still so small in comparison to other items that it has very little impact on the overall profitability. For the purpose of comparing alternatives, the ranking between alternatives does not change as a result of changes in discount rate for this application.

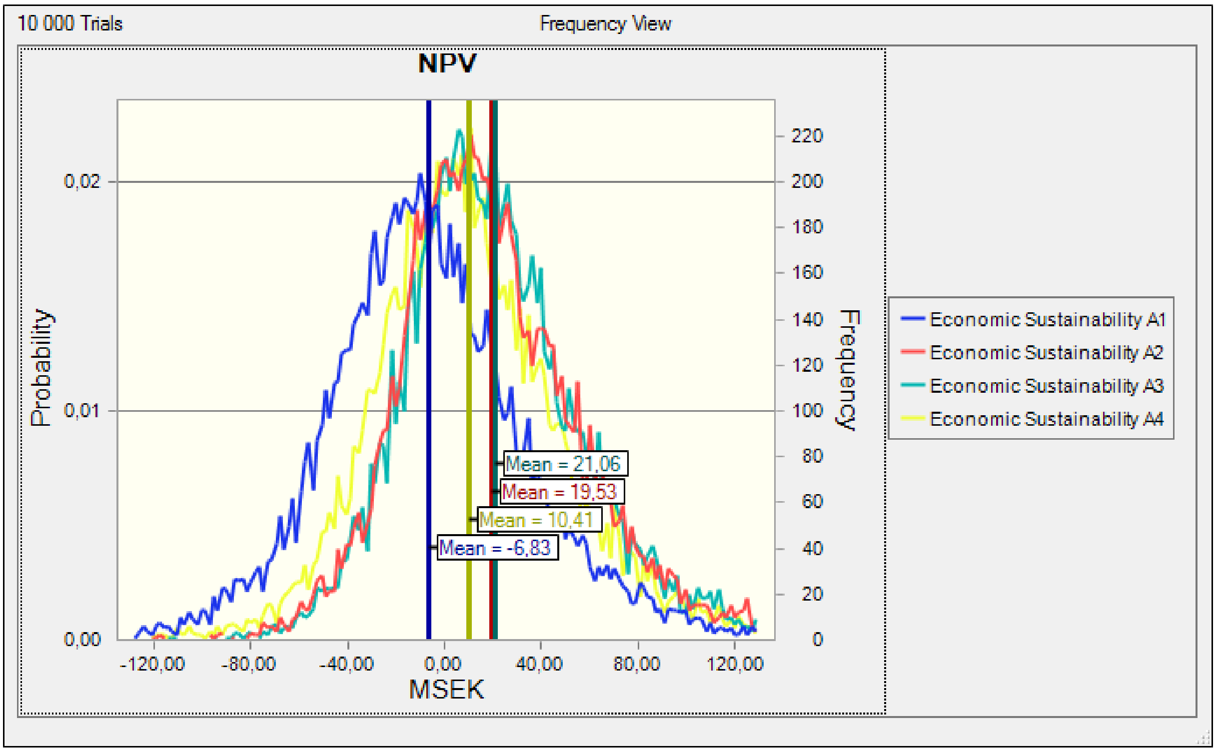

Figure 9. Simulation results for NPV for the four remediation alternatives given a zero discount rate.

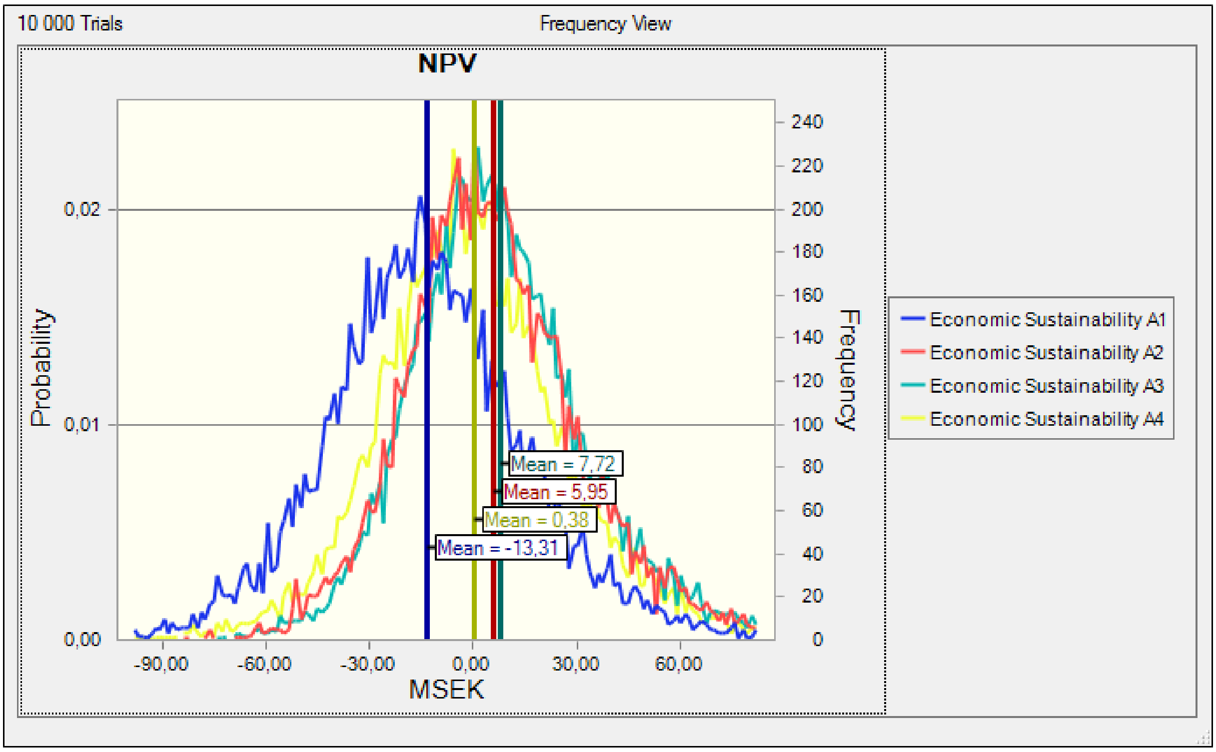

Figure 10. Simulation results for NPV for the four remediation alternatives given a 7 % discount rate.

5. Concluding discussion

We have shown how a CBA based on theoretical cost-benefit rules can be applied to the case of remediation of contaminated land for investigating to what extent a remediation alternative is socially profitable, or at least ranking remediation alternatives with respect to *NPV*. The impact of uncertainties on the CBA result was also illustrated, including the potential impact of correlations between benefit and cost items. Communicating the uncertainty associated with *NPV*, including explanations of what items is contributing the most to this uncertainty, is likely to be of considerable importance for decision-makers when making a choice of a remediation alternative. Further, the application to the Hexion site highlighted that there are both positive and negative consequences of remediation, and also the importance of considering different remediation alternatives. For this site, only the extensive excavation alternative 1 had a negative expected *NPV*. This is mainly due to the fact that it involved higher remediation costs than the other alternatives, but it also involved the most substantial negative externalities.

Social profitability as evaluated by CBA is one type of information that can help assessing remediation alternatives. Still, SCORE is an MCA tool in which CBA is complemented with other types of assessments for finding out to which extent a remediation alternative fulfills a number of environmental and social criteria, see Rosén et al. (2014) for details. This is because CBA is associated with quite particular ethical and theoretical points of departure and can therefore not be expected to give complete information for decision-makers about the sustainability of a remediation alternative. For example, CBA relies in several respects on utilitarianism because of its focus on consequences and its aggregation of costs and benefits across different actors. The theoretical foundation of CBA in welfare economics also allows weighting of different effects through monetization based on individual preference satisfaction (Hausman and McPherson, 2006). It has been suggested that this is consistent only with one of several roles that individuals can have (Sagoff, 2007). That CBA is applied in an MCA context acknowledges ethical pluralism, and societal decision-making typically has to combine different ethics for arriving at reasonable normative judgments (Weber, 1919 [1958]).

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SCORE: Multi-Criteria Decision Analysis for Assessing the Sustainability of Remediation at Contaminated Sites

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Paper III

SCORE: Multi-Criteria Decision Analysis for Assessing the Sustainability of Remediation at Contaminated Sites

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ABSTRACT

For comprehensive and transparent assessment of sustainability, multi-criteria decision analysis (MCDA) is often suggested. Development of a relevant MCDA-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 assessment 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) MCDA-method was developed to provide a transparent assessment of the sustainability of possible remediation alternatives for contaminated sites relative to a reference alternative, considering key criteria in the economic, environmental and social sustainability domains. The criteria were identified based on literature studies, interviews and focus-group meetings. One key criterion was applied to the economic domain: Social profitability, evaluated by cost-benefit analysis. The environmental criteria are: Soil, Flora and fauna, Surface water, Groundwater, Sediment, Air, Non-recyclable waste and Non-renewable natural resources. The social 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 a non-compensatory approach to identify alternatives regarded as non-sustainable. The key strengths of the SCORE method are: a framework that at its core is designed to be flexible and transparent; its ability to integrate quantitative and qualitative estimations of criteria, the inclusion of a full uncertainty analysis of the results, using Monte Carlo simulation; and a structure that allows preferences and opinions of involved stakeholders to be openly integrated into the analysis.

1. 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 can 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 methods for evaluating the environmental footprint of remedial actions. The Sustainable Remediation Forum in the United Kingdom (SuRF UK, 2010; 2011) suggested a framework and indicators (criteria) for a comprehensive sustainability assessment of remedial actions, considering positive and negative environmental, economic and social effects. The Network for Industrially Contaminated Land in Europe (NICOLE) also suggested a framework for sustainability assessment (NICOLE, 2012). During 2004-2009 the Swedish EPA (2009a) performed a program comprising more than 50 projects on sustainable remediation. The International Standard Organization (ISO) currently works on an informative standard for sustainable remediation of contaminated land.

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 assessment (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 qualitative and quantitative information into a comprehensive evaluation. MCA has been suggested for sustainability assessment of remedial actions by a number of authors, e.g. Harbottle et al. (2008), Alvarez-Guerra et al. (2009), Rosén et al. (2009), Linkov & Moberg (2011), Brinkhoff (2011), Sparrevik et al. (2012), and Smith & Kerrison (2013).

MCA is a general term which includes a number of different methods, e.g. linear additive, multi-attribute, outranking, and non-compensatory methods, see e.g. Belton & Stewart (2002) and DCLG (2009) for overviews of various MCA methods. MCA methods can be qualitative, quantitative or semi-quantitative. When numerical values are used for scoring and weighting of criteria in order to facilitate comparison of alternatives, the term multi-criteria decision analysis (MCDA) is sometimes used.

Development and application of MCA/MCDA-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/MCDA applications are the lack of uncertainty analysis, unclear definitions of system boundaries, overlapping of criteria resulting in double-counting of effects, and unclear definitions of performance scales (see e.g. Belton & Stewart, 2002).

We argue in this paper that successful application of MCA/MCDA for sustainability assessment of remediation alternatives requires (1) a clear conceptual model of the major components and boundary conditions of the assessment, (2) clear definition of sustainability, (3) a set of key criteria with well-defined performance scales from which criteria relevant for the particular study can be selected without, or as little as possible, double-counting of effects, (4) clear and transparent handling of uncertainties, and (5) a structured stakeholder involvement in the assessment process.

The purpose of this paper is to present the Sustainable Choice Of REmediation (SCORE) MCDA-method and provide an example of application. SCORE was developed to avoid common shortcomings of MCDA methods in order to provide a relevant and transparent assessment of the sustainability of remediation alternatives relative to a reference alternative, considering key criteria in the economic, environmental and social sustainability domains. To our knowledge, SCORE is unique in (1) integrating social and environmental analyses of remediation alternatives with a fully quantitative economic analysis, (2) evaluating remediation alternatives with respect to strong and weak sustainability on both sustainability domain and criteria levels, (3) allowing weighting of sustainability domains to reflect different views of sustainable development, (4) providing a gross set of non-overlapping key performance criteria, and (5) providing a full uncertainty analysis of MCDA outcomes, into one single method. To facilitate practical application of SCORE, a computer tool (in Excel) has been developed and the example shown in this paper was performed using the SCORE tool.

2. THE SCORE METHOD

2.1. Sustainability

It was assumed that the sustainability of a remedial action can be relevantly assessed by evaluating its performances in the *economic*, *environmental* and *social* domains, consistent with the perspectives on sustainable development repeatedly emphasized by, for example, the United Nations (e.g., UN, 2012). 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 different components of the assessment or not and distinguishes between development towards *weak* and *strong* sustainability, see e.g. Pearce et al., (2006). 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 contribute in a substitutable way to human well-being (Arrow et al., 2003; Bond & Morrison-Saunders, 2011). Weak sustainability implies that negative impacts in e.g. the environmental domain can be compensated by positive performance in the economic domain. It thus might imply that irreversible impacts in the environmental, the social 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) and that compensation is not allowed. Most attention has been paid towards the fundamental role of natural capital, implying that at least critical components of this type of capital have to be conserved (Pearce et al., 2006).

In the literature on sustainable remediation, the dominating model is a Venn diagram of overlapping circles, which implies that that all three sustainability domains are equally important, see Figure 1. Sustainable solutions exist in the area where all three domains overlap. Another common view is the “bull’s eye” model (Figure 1), which implies that the environment is the fundamental domain without which humans cannot exist (see e.g. Scott Cato, 2009). Within the environmental domain there is a social domain, which in turn includes an economic domain. This view implies that the environmental domain is the most important and the economic domain is the least important for sustainable development.

SCORE identifies compensatory effects on both the domain and criteria levels. It is up to the assessment team to define what type of sustainability, in terms of strong and weak sustainability on domain and criteria-levels, that is required for the particular assessment. SCORE also provides a possibility to reflect different views on the relative importance of the three domains by assigning different weights to the domains in the comprehensive sustainability assessment of remediation alternatives.

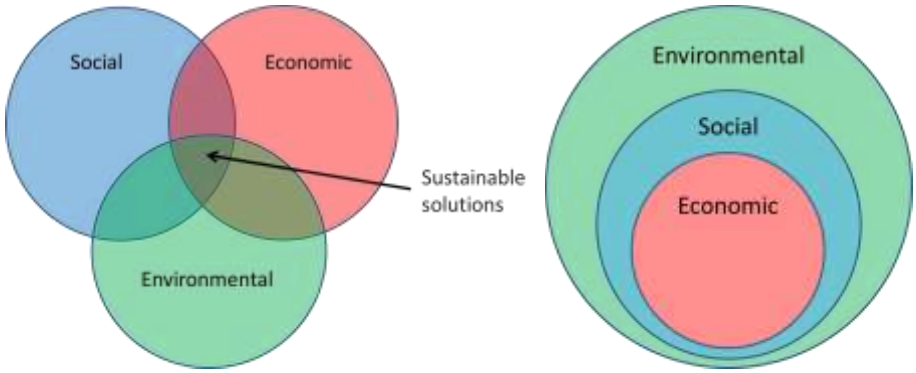


Figure 1. *Two common sustainability models, "Venn diagram" model (left) and "Bull's eye" model (right).*

2.2. The SCORE framework

The SCORE framework (Figure 2) was developed in line with the view on the decision-making process of Aven (2003).

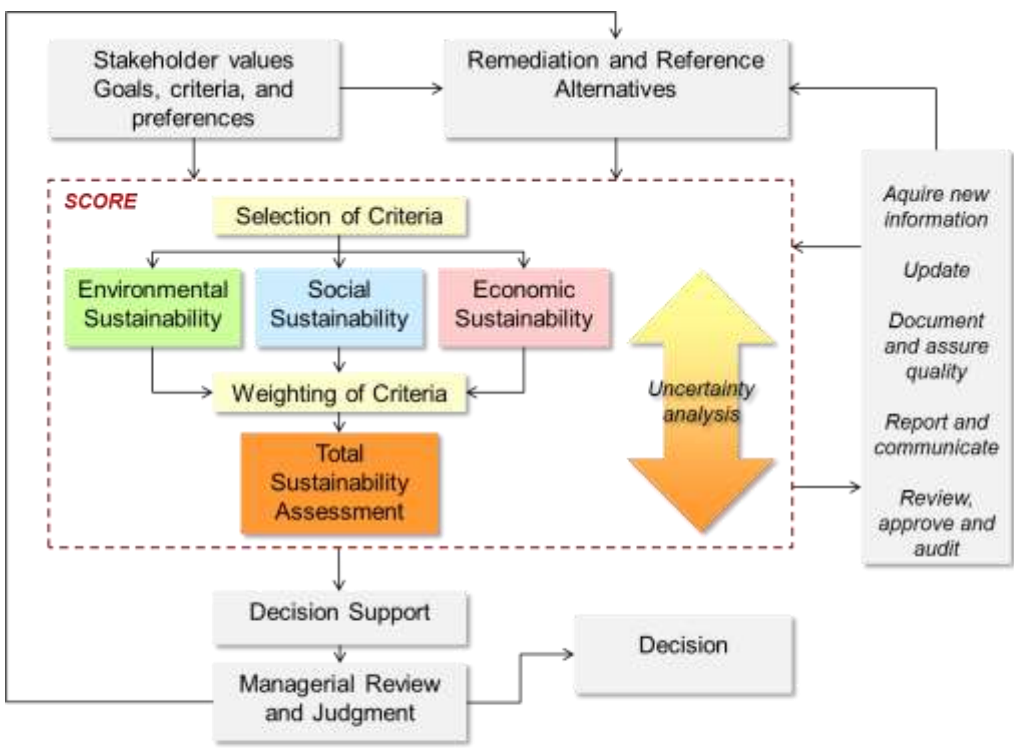


Figure 2. *The SCORE decision support framework.*

SCORE provides decision support when choosing between a set of remediation alternatives. The expected effects of remediation 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 *a non-compensatory approach* to distinguish between alternatives expected to lead to strong and weak sustainability, respectively. The functionalities of the *linear additive* and *non-compensatory* approaches are explained in Section 2.5 below. Uncertainty assessment is performed for each scoring and quantification, facilitating uncertainty and sensitivity analyses of the outcomes. SCORE also identifies possibilities on *how to improve* the sustainability of studied remediation alternatives. The method thus has an iterative approach, encouraging updating as new information becomes available.

2.3. Conceptual model and assessment boundaries

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 MCDA 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. 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 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 3) to provide a relevant structure for the MCDA, 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* at hand are (1) the change in *source contamination*, typically resulting in positive effects in terms of reduced risks to humans and ecosystems and possibilities for new land utilization, and (2) 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*, *ecosystems*, and *natural resources*. The main types of both *long-term and short-term effects* are environmental, economic and social effects.

The current system boundary of SCORE limits the assessment to situations with transformation 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. This would require a wider social assessment, considering e.g. segregation, gender, and security (crime) issues. Given a fixed future land-use scenario, the user has to define in detail the system, LCA, temporal and spatial boundaries specific to the particular assessment.

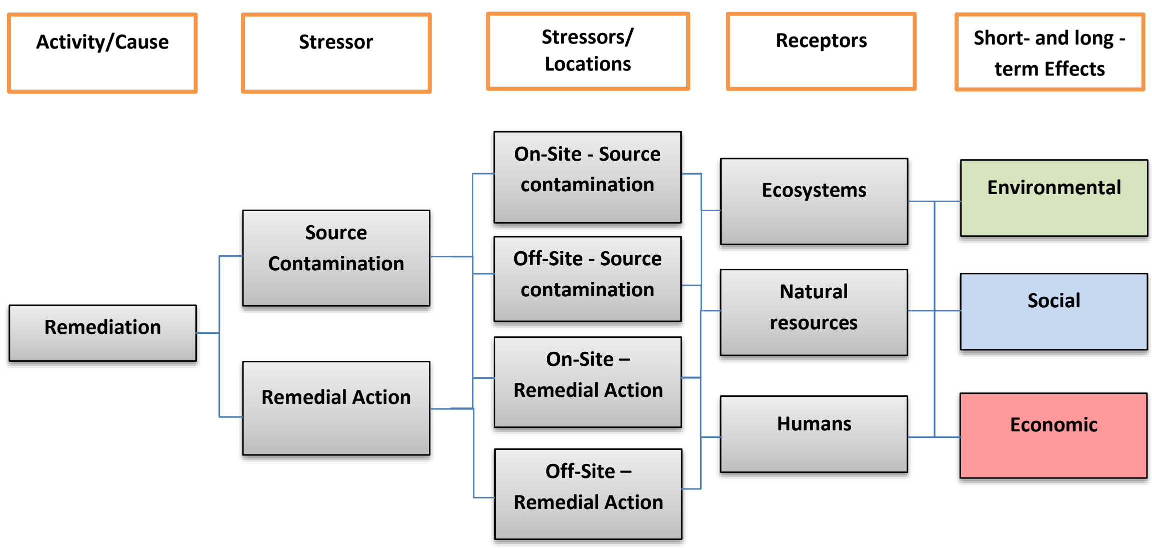


Figure 3. *Conceptual Model of SCORE.*

2.4. Key Performance Criteria

According to e.g. Van den Bergh (2010) there are some critical aspects in each sustainability domain that cannot be substituted by others. Furthermore, there is a common understanding that “sustainability” in its entirety cannot be quantified in absolute terms (NICOLE and Common Forum, 2013). Accepting this, the purpose should be to select key performance criteria for each sustainability domain of the MCDA, given the defined boundary conditions, which are mutually exhaustive and thus capable of collectively representing all key sustainability aspects, while at the same time avoiding double-counting of effects.

The selection of the key performance criteria was based on extensive literature reviews, interviews during an expert group workshop (Brinkhoff, 2011), focus group meetings in Sweden (Norrman & Söderqvist, 2013), and an earlier prototype of the method (Rosén 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* (SC) and the *remedial action* (RA), respectively. The on-site/off-site boundary has to be defined by the assessment team but is typically the property boundary of the site. By applying the conceptual model shown in Figure 3, with clear distinctions between activity, stressors, spatial locations and receptors as a basis for the process of identifying key criteria, it was assumed that the risk of double-counting effects would be effectively reduced.

Table 1. *Key performance criteria for each sustainability domain in SCORE.*

Environmental domain	Social 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 and safety • Local participation • Local acceptance	• Social profitability

Double-counting should not be confused with inevitable dependencies between effects among the domains. For example, environmental change might have both economic and social effects. The domains can still give complementary information because they reflect ethical pluralism, i.e. an MCDA method such as SCORE can be a way of approaching incommensurability of values (Spash, 2013). Intrinsic values in nature are one main ethical motive for having a separate environmental domain (Des Jardins, 2013), and the social domain could reflect duty-based ethics such as people's rights to good health (WHO, 2006), while the economic domain has utilitarianism and welfare economics as a basis in the sense that it allows weighting of different effects through monetization based on individual preference satisfaction (Hausman and McPherson, 2006). The difference between the social and economic domains might also be reflected by individuals having different roles in a social and economic context, respectively (Sagoff, 2007).

Environmental criteria

A schematic illustration of the spatial locations of the key criteria in the environmental domain is presented in Figure 4 and short descriptions are given in Table 2.

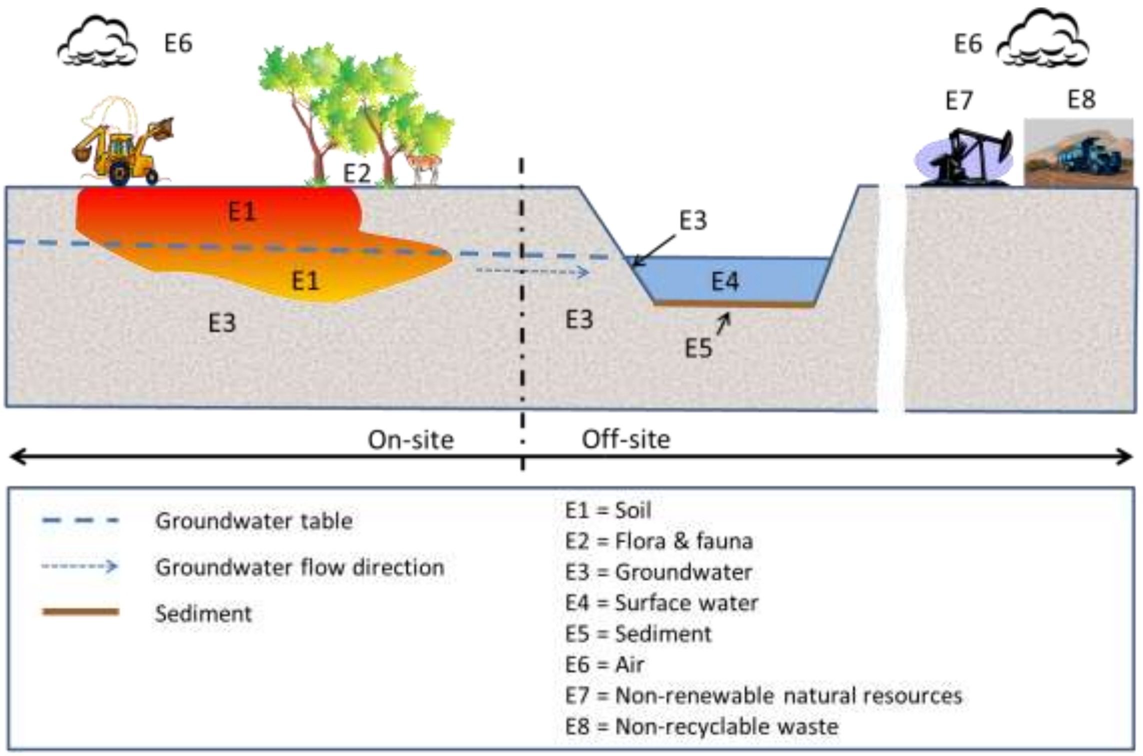


Figure 4. *Schematic illustration of the environmental key criteria in SCORE and their spatial locations.*

Sub-criteria for soil were identified assuming that ecotoxicological risks from exposure to the contaminated soil and soil functions, as defined here (see Volchko et al., 2013; 2014), are independent and that soil functions therefore are potentially affected by the remedial action only. Ecotoxicological risks in soil were assumed to be potentially affected by the change in source contamination, but possibly also so from the remedial action itself. An example of an impact from the remedial action is storing of toxic soil or waste in an uncontaminated portion of the site causing potentially increased risks for the soil ecosystem. It was further assumed that ecotoxicological risks and soil functions off-site are not impacted by the remediation.

Table 2. *Criteria in the Environmental domain (RA = Remedial action; SC = Source contamination).*

Key Criteria	Description	Sub-criteria
E1. Soil	The soil criterion is divided into an *ecotoxicological risk* due to the soil contamination and a *soil function* component. The ecotoxicological risk reflects the effects on the soil ecosystems due to the change in source contamination and/or to impacts of the remedial action. The soil function assessment is directed at evaluating the effects of the remedial action on soil's capability of providing good pre-conditions for organisms, taking into account factors such as soil texture, pH, organic content, availability of nitrogen and carbon, and water retention capacity. Extensive descriptions of the soil function assessment included in SCORE are given by Volchko (2013) and Volchko et al. (2013; 2014).	Ecotox risk RA On-site Ecotox risk SC On-site Soil function RA On-site
E2. Flora & fauna	Physical impacts on e.g. trees, birds and mammal habitats from the remedial action.	Flora & fauna RA On-site
E3. Ground-water	Effects on groundwater quality and ecotoxicological risks in the discharge zone to e.g. wetland areas potentially affected by the source contamination and/or the remedial action.	Groundwater RA On-site Groundwater RA Off-site Groundwater SC On-site Groundwater SC Off-site
E4. Surface water	Effects on surface water quality and ecotoxicological risks in the water zone of surface water bodies and streams potentially affected by the source contamination and/or remedial action.	Surface water RA On-site Surface water RA Off-site Surface water SC On-site Surface water SC Off-site
E5. Sediment	Effects on ecotoxicological risks for organisms in sediments potentially affected by the source contamination and/or remedial action.	Sediments RA On-site Sediments RA Off-site Sediments SC On-site Sediments SC Off-site
E6. Air	Total emissions to air, including greenhouse gases, acidifying substances, and particulate matter, due to the remedial action.	Air RA
E7. Non-renewable natural resources	Total use of non-renewable energy due to the remedial action.	Non-renewable natural resources RA
E8. Non-recyclable waste	Total production of non-recyclable waste due to the remedial action.	Non-recyclable waste RA

Flora & fauna were assumed to be potentially affected by the remedial action on-site only. An example is that trees with a high protection value or with nesting places for protected bird species have to be removed by the remedial action. Further, it was assumed that groundwater, surface water and sediments can be affected both due to the change in source contamination and due to the remedial action on-site and off-site. The effects on air, non-renewable natural resources and non-recyclable waste were assumed to be associated with the remedial action only and were not divided spatially.

In the selection of the sub-criteria shown in Table 2 it was assumed that the disposal and/or treatment facility is designed and functioning in such a way that the particular remediation at hand does not have any additional effects on soil, flora & fauna, groundwater, surface water or sediments, at the disposal/treatment site. Note that the suggested list of environmental key and sub-criteria in Table 2 represents a reasonable balance between completeness and practicality, given the results of interviews, focus group meetings and the professional judgments of the development team. However, there are no restrictions on adding sub-criteria to e.g. represent separate effects on-site and off-site on soil, flora & fauna, air, or waste production.

Social criteria

Like the environmental criteria, the social criteria are divided into sub-criteria relating to effects due to the remedial action (RA) itself or effects due to the change in source contamination (SC). Short descriptions of key criteria in the social domain are given in Table 3.

Some of the social effects that arise are related to the change in land use that is made possible by the remediation alternative, rather than due to the actual changes in the source contamination. Although the social criteria in SCORE were not developed to support decisions on land use planning (see discussion in section 2.3 on the conceptual model of SCORE), this does not mean that the land use change implied by a remediation will not have an impact on the scoring in the social domain. In fact, for some aspects the change in land use may represent the largest effect, larger than of the actual remediation strategy. The social effects are scored in relation *to where* they will arise, which in this case sometimes also means in relation *to who* they will affect, i.e. on-site and off-site effects. For example, the sub-criterion *Health and safety RA on-site* relates to workers' health and safety during the remedial action, whereas sub-criterion *Health and safety RA off-site* relates to how neighbours to the site are affected by the remedial action. The criterion *Equity* takes intra- *and* intergenerational equity into consideration and therefore the effects due to changes in SC should be scored with regard to future generations affected by the site.

Table 3. *Criteria in the Social domain (RA = Remedial action; SC = Source contamination).*

Criteria	Description	Sub-criteria
S1. Local environmental quality (LEQ) and amenity, including physical disturbances	Effects on e.g. recreational values, noise or/and the accessibility of the area.	LEQ RA On-site LEQ RA Off-site LEQ SC On-site LEQ SC Off-site
S2. Cultural heritage	Effects on cultural heritage items due to destruction, preservation or restoration, but *not* with regard to the increased access to those items that can be expected from a change in SC and subsequent change in land-use (this is scored in S1).	Cultural heritage RA On-site Cultural heritage RA Off-site
S3. Health and safety	Effects on human health and safety due to exposure and spreading of contaminants in soil, dust, air, water and due to accidental risks (e.g. traffic).	Health and safety RA On-site Health and safety RA Off-site Health and safety SC On-site Health and safety SC Off-site
S4. Equity	Effects on vulnerable groups in the society.	Equity RA On-site Equity RA Off-site Equity SC On-site Equity SC Off-site
S5. Local participation	Effects on how the local community is affected with regard to local job opportunities or other local activities. This criterion does *not* relate to participation of the local community in the remediation decision process.	Local participation RA On-site Local participation RA Off-site Local participation SC On-site Local participation SC Off-site
S6. Local acceptance	Effects with regard to the acceptance of the remediation alternative by the local community. It should be noted that the local acceptance for activities can be improved by open information, dialogue and/or participation processes carried out in an appropriate way.	Local acceptance RA On-site Local acceptance RA Off-site Local acceptance SC On-site Local acceptance SC Off-site

Economic criterion

The key criterion of the economic domain is social profitability assessed by means of cost-benefit analysis (CBA), being a well-defined and widely applied technique for evaluating economic consequences for society (Pearce et al., 2006; Rosén et al., 2008). The cost and benefit items included in SCORE are shown in Table 4. The social profitability is calculated in monetary terms as a net present value (*NPV*) over the time horizon of the remediation project (see section 2.5).

Table 4. *Benefits (B) and costs (C) in the economic assessment of SCORE.*

Main items of benefits and costs	**Sub-items of benefits and costs**
B1. Increased property value on site	
B2. Improved health	B2a. Reduced acute health risks
	B2b. Reduced non-acute health risks
	B2c. Other types of improved health, e.g. reduced anxiety
B3. Increased provision of ecosystem services	B3a. Increased recreational opportunities on site
	B3b. Increased recreational opportunities in the surroundings
	B3c. Increased provision of other ecosystem services
B4. Other positive externalities than B2 and B3	
C1. Remediation costs	C1a. Design of remedial actions
	C1b. Project management
	C1c. Capital costs
	C1d. Remedial action
	C1e. Monitoring
	C1f. Project risks
C2. Impaired health due to remedial action	C2a. Increased health risks on site
	C2b. Increased health risks from transports activities
	C2c. Increased health risks at disposal sites
	C2d. Other types of impaired health, e.g. increased anxiety
C3. Decreased provision of ecosystem services due to remedial action	C3a. Decreased provision of ecosystem services on site
	C3b. Decreased provision of ecosystem services in the surroundings
	C3c. Decreased provision of ecosystem services at disposal sites
C4. Other negative externalities than C2 and C3	

While some events with an uncertain outcome might have been prevented through, for example, site investigations and project management, some probabilistic costs are likely to remain (cost item C1f). Such project risks might be associated with the remediation method (e.g. the remedial design turns out to be inappropriate or inefficient), authorities (e.g. remediation permits are delayed), public opinion (e.g. additional information about the remediation turns out to be necessary to communicate), project organization and financial structure (e.g. the project organization has communication problems that could affect the efficiency of the remediation measure), technical basis for assessment (e.g. the volume of the contaminant is found to be underestimated), and liability issues (e.g. the contaminant unexpectedly affects an adjacent lot). A guidance and probabilistic model is being developed for quantification of project risks.

Since each cost and benefit item represents the quantitative sum of all economic consequences resulting from a particular effect, there is no need for any spatial sub-division of items similar to the environmental and social domains. SCORE provides for a distributional analysis, in which the *NPV* for different actors is studied. The assessment team therefore needs to assign the main beneficiary or payer for each cost and benefit item. The distributional analysis is a necessary part of the CBA in order to provide a basis for fair distribution of costs and benefits among involved stakeholders. A more detailed description of the cost and benefit items and the various capabilities and limitations of the CBA will be provided in a separate publication.

2.5. Sustainability Assessment

Remediation and reference alternatives

Remedial alternatives evaluated by SCORE must be specified prior to performing the MCDA and all effects (impacts) are assessed relative to a *reference alternative*. It is up to the assessment team 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 meeting remediation targets (mostly defined by authorities), 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 should be considered. The constraints are project specific and they are not part of the MCDA. The reference alternative does not have to be an acceptable alternative (for example, often the no action alternative is not possible since it is required that some action is taken to improve the situation), but serves as a position against which acceptable alternatives are evaluated and compared. Note that the reference alternative cannot include remediation, since that would lead to invalid assessment of some criteria, most notably E6-E8.

Selection of criteria

The SCORE assessment starts by selecting relevant key and sub-criteria for the analysis. Relevant cost and benefit items to be included in the CBA are selected from the gross list provided in SCORE, see description in section 2.4. In case that criteria or cost-benefit items are chosen to be excluded from the assessment, this has to be clearly motivated by the assessment team. We believe that a full bottom-up approach, in which the assessment team selects a set of criteria based on stakeholder analyses or professional judgment, is associated with substantial risk of double-counting of effects and unbalanced sustainability assessments. Instead, we recommend that the gross list of criteria, sub-criteria and cost-benefit items included in SCORE is used as a starting point and that exclusions from this list is clearly motivated.

Performance scales

Scoring of effects (criteria) in the environmental and social domains is performed using the following semi-quantitative (ordinal) performance scale: 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 scorings are performed using available data, expert judgment, questionnaires, and/or individual or group interviews. The scoring procedure is supported by a guidance matrix for each criterion with examples as a basis for the assessment. Example of a guidance matrices are shown in Table 5 (for the environmental domain) and Table 6 (for the social domain). For each key criterion there are also key questions to address and suggestions of key information to collect as a basis for the scoring. The assessment team has to assign the score that best represents the expected effect, given the available information and knowledge. Each scoring has to be shortly motivated for transparency.

Cost and benefit items of the CBA are monetized to the greatest extent possible, given the constraints of the assessment. All items identified as relevant but not possible to monetize are assessed as being *somewhat important* or *very important*, allowing for a qualitative assessment of these items and the outcomes of the CBA.

Table 5. *Example of scoring guidance matrix in SCORE for effects on sediments.*

Very negative effect: -6 to -10	Negative effect: -1 to -5	No effect: 0	Positive effect: +1 to +5	Very positive effect: +6 to +10
Severe impact on sediment conditions with strong negative effects on the ecosystem functions.	**Impact on sediment conditions with strong negative effects on the ecosystem functions.**	**No or negligible impact on sediment conditions and ecosystem functions.**	**Impact on sediment conditions leading to improvement of ecosystem functions.**	**Impact on sediment conditions leading to extensive improvement of ecosystem functions.**
Example, Remedial action: Contamination of sediments due to leaching from stockpiles of contaminated soil, resulting in a strong negative effect on the ecosystem functions. *Example, Remedial action:* Contamination of sediments from excavation of contaminated soil/sediments in water, resulting in a strong negative effect on ecosystem functions. *Example, Source contamination:* Long-term contamination of sediments due to release of contaminants from a sedimentation pond, resulting in a strong negative effect on ecosystem functions.	*Example, Remedial action:* Contamination of sediments due to leaching from stockpiles of contaminated soil, resulting in a negative effect on the ecosystem functions. *Example, Remedial action:* Contamination of sediments from excavation of contaminated soil/sediments in water, resulting in a negative effect on ecosystem functions. *Example, Source contamination:* Long term contamination of sediments due to release of contaminants from a sedimentation pond, resulting in a negative effect on ecosystem functions.	*Example, Remedial action:* The remediation will have a neglible effect on contaminant concentrations in the sediments.	*Example, Remedial action:* No such case has been identified. *Example, Source contamination:* Positive effects on ecosystem functions after removal of the most contaminated sediments. *Example, Source contamination:* Reduced contaminant concentration in surface water, resulting in improved long-term living conditions for plants and animals in the sediments.	*Example, Remedial action:* No such case has been identified. *Example,Source contamination:* Strong positive effects on ecosystem functions after removal of the most contaminated sediments. *Example, Source contamination:* Reduced contaminant concentration in surface water, resulting in strongly improved long-term living conditions for plants and animals in the sediments.

Table 6. *Example of scoring guidance matrix in SCORE for effects on local environmental quality and amenities.*

Very negative effect: -6 to -10	Negative effect: -1 to -5	No effect: 0	Positive effect: +1 to +5	Very positive effect: +6 to +10
The local environmental quality and amenities will be impacted very negatively by the remediation alternative compared to the reference alternative	**The local environmental quality and amenities will be impacted negatively by the remediation alternative compared to the reference alternative**	**The local environmental quality and amenities will not be impacted by the remediation alternative compared to the reference alternative**	**The local environmental quality and amenities will be impacted positively by the remediation alternative compared to the reference alternative**	**The local environmental quality and amenities will be impacted very positively by the remediation alternative compared to the reference alternative**
Example: The local environmental quality off-site will be impacted very negatively by the remediation alternative as a result of the remedial action due to extensive physical disturbances, e.g. the heavy transport will reduce the accessibility to amenities in the surrounding or give raise to very extensive noise. *Example:* The site has a high recreational value (e.g. bird-watching or other) and due to the remedial action, the remediation alternative will result in an extensive decrease in recreational value.	*Example:* The local environmental quality off-site will be impacted negatively by the remediation alternative as a result of the remedial action due to physical disturbances, e.g. the heavy transport will reduce the accessibility to amenities in the surrounding or give raise to noise. *Example* : The site has some recreational value (e.g. bird-watching or other) and due to the remedial action, the remediation alternative will result in a decrease in recreational value.	Example: Since the reference alternative already is associated with extensive physical disturbances to the surrounding area (off-site), the remedial action will not result in any significant effect compared to the reference alternative.	*Example:* The local environmental quality on-site will be impacted positively due to the change in landuse which will be a result of the change in source contamination. *Example:* The site has some recreational value and the remediation alternative will result in increased access to the site compared to the reference alternative, as a result of the change in source contamination. *Example:* The remediation alternative will result in an improved recreational quality off-site, e.g. by making a nearby swimming area possible to be used, as a result of the change in source contamination.	*Example:* The local environmental quality on-site will be impacted very positively due to the change in landuse which will be a result of the change in source contamination. *Example:* The site has a high recreational value and the remediation alternative will result in highly increased access to the site compared to the reference alternative, as a result of the change in source contamination. *Example:* The remediation alternative will result in a highly improved recreational quality off-site, e.g. by making a nearby swimming area possible to be used by a large number of people, as a result of the change in source contamination.

Environmental assessment

The environmental effects are typically scored based on existing information, such as ecological risk assessments, samplings and laboratory analyses, soil function assessment (see Volchko et al., 2014), inventories of recipient conditions, and risk analyses of the remedial action, e.g. the risk of spill to a nearby stream from a dam for collecting contaminated groundwater. Scoring of effects on air, non-renewable natural resources and production of non-recyclable waste are based on footprint analyses, e.g. quantifications of air emissions, use of non-renewable fuels, and production of non-recyclable waste.

For criteria E1 to E5 scorings are based on qualitative guidance on very negative, negative, no, positive or very positive effects, see *Performance scales* above. For criteria E6 to E8 the scoring is based on quantitative values relative to a remedial action with complete excavation and disposal of all contaminated soil off-site, using standard excavation, transport and disposal techniques, non-renewable energy, non-renewable materiel, juvenile filling materials and disposal of all contaminated material. As noted earlier, in the suggested gross criteria list in SCORE, key criteria E2 and E6-E8 consider effects due to the remedial action only, whereas other criteria consider effects due to both the change in source contamination and the remedial action.

Social assessment

With regard to the social criteria, S1 to S5 are formulated such that they can be scored by experts, whereas criterion S6 – local acceptance – is a criterion that should reflect how the local community actually perceives the different remedial strategies. The social effects on S1 to S5 are scored based on existing information, e.g. the human health risk assessment, environmental impact assessment, existing documentation on cultural heritage, but also e.g. on the distributional analysis within the CBA (see below), and stakeholder analysis. However, input from experts is crucial and people with local knowledge should be involved in the scoring of the social criteria. For example, (local) experts on cultural heritage and protection should advice the scoring relating to S2. Scoring for S6 on the other hand, should consult the local community directly. All scoring is made according to qualitative guidance on very negative, negative, no, positive or very positive effects, see *Performance scales* above.

Economic assessment

The net present value (*NPV*) of a remediation alternative *i* is computed as follows:

$$NPV_i = \sum_{t=0}^{T} \frac{1}{(1+r_t)^t} (B_{i,t} - C_{i,t}),$$ (Eq. 1)

where $B_t = B1_t + B2_t + B3_t + B4_t$ and $C_t = C1_t + C2_t + C3_t + C4_t$ (see Table 4), i.e. the sum of benefits and costs at time *t* (usually years), r_t is the social discount rate at *t*, and *T* is the time horizon associated with the benefits and costs. Given that all costs and benefits have been monetized and thus are included in the *NPV* computation, the remediation alternative associated with the highest *NPV* is the most profitable one to society (or, if $NPV<0$, the one that gives the least social loss).

In many cases all costs and benefits cannot be monetized and it is therefore important to also provide a qualitative discussion concerning non-monetized items. Guidance and a calculation model has been developed for how to monetize each item in the CBA, providing information and recommendations of suitable valuation approaches for the specific item.

A SCORE user may wish to only include a subset of the cost and benefit items in Table 4. For example, an alternative to perform a full CBA may be to focus on the cost side only, using a cost-effectiveness (CEA) approach. A CEA approach can be used if all studied alternatives are expected to reach the goal of the remediation (e.g. to reach acceptable risk levels), if the benefits of the alternatives are similar, and if it is not required that $NPV>0$. The output of a CEA used in a SCORE assessment is the present values of the total costs of the alternatives. As another example, a developer might be interested in delimiting the analysis to the cost and benefit items that are directly related to financial flows (primarily B1 and C1) and can thus choose to delimit the economic assessment accordingly.

Weighting of criteria

Each key criterion and sub-criterion in the environmental and social domains is weighted with respect to their relative importance. The importance *I* of each key criterion *k* ($k=1\ldots K$) in domain *D* is given a numerical value according to the following scale: somewhat important = 1; important = 2; very important = 3. The weight of the key criterion is calculated as:

$$w_{k,D} = \frac{I_{k,D}}{\sum_{k=1}^{K} I_{k,D}}$$ (Eq. 2)

The importance I of each sub-criterion j (j=1…J) included in key criterion k (k=1…K) is given a numerical value according to the following scale: somewhat important = 1; important = 2; very important = 3. The weight of each sub-criterion is calculated as:

$$w_{j,k} = \frac{I_{j,k}}{\sum_{j=1}^{J} I_{j,k}} \quad \text{(Eq. 3)}$$

The weights of sub-criteria and key criteria thus have a value [0,1] and the total weight of all criteria (sub-criteria and key criteria, respectively) sum to 1.

For each remediation alternative i (i=1…N) a sustainability index H is calculated for each domain D as the weighted sum of the scorings using a linear additive approach:

$$H_{D,i} = \sum_{k=1}^{K} w_{k,D} \sum_{j=1}^{J} w_{j,k,D} Z_{j,k,D} \quad \text{(Eq. 4)}$$

where w_j is the weight of sub-criterion j and Z is the score of the sub-criterion j. The weighting is performed by the assessment team, taking into consideration judgments and opinions of experts and stakeholders.

In the economic domain, weighting of benefits and costs is carried out through the monetization in the NPV calculation.

Sustainability index

A normalized sustainability score, H, is calculated for each alternative i as:

$$H_i = 100 \left[\begin{array}{l} W_E \dfrac{H_{E,i}}{Max\left[Max(H_{E,1..N});\left|Min(H_{E,1..N})\right|\right]} + W_{SC} \dfrac{H_{S,i}}{Max\left[Max(H_{S,1..N});\left|Min(H_{S,1..N})\right|\right]} \\ + W_{NPV} \dfrac{NPV_i}{Max\left[Max(NPV_{1..N});\left|Min(NPV_{1...N})\right|\right]} \end{array} \right] \quad \text{(Eq. 5)}$$

where E is the score in environmental domain, S is score in the social domain, NPV is the net present value, and W is the weight of each domain. The weights of the domains are assigned according to the same scale as for the criteria. 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.

SCORE uses a non-compensatory approach to check whether there is compensation on the criteria and/or domain levels, i.e. identifies alternatives of *weak* and *strong* sustainability. The assessment team has to clearly define type of sustainability required. Ranking and final selection are then made among alternatives that meet the sustainability definition. A major asset of SCORE is thus that it clearly identifies which criteria, if any, that should be improved in order to meet a specific definition of sustainability.

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.

The treatment of uncertainty in SCORE follows a Monte Carlo simulation approach, where statistical distributions represent the uncertainties in scores and cost-benefit items. Uncertainties are estimated based on professional judgment by the assessment team. Uncertainties in scores are represented by beta distributions and uncertainties in cost and benefit items are represented by log-normal distributions.

The assignment of the scoring uncertainty distribution (beta) is performed in three steps: (1) selection of the possible range of scorings for the specific sub-criterion; the scoring intervals are -10 to +10 if the entire scoring range is possible, -10 to 0 if no positive effects are possible, and 0 to +10 if no negative effects are possible, (2) estimation of the most likely score using the performance scale presented above, and (3) assigning the uncertainty category level of the estimation of the most likely effect; high, medium or low. The three-step procedure results in a scaled beta probability distribution representing the uncertainty of the scoring of the sub-criterion. Based on discussions within the development team uncertainty categories for scores are represented by standard deviation values shown in Table 6. The basic idea was that the uncertainty interval representing *high* uncertainty should be twice the uncertainty interval representing *low* uncertainty. The uncertainty interval representing *medium* uncertainty is in the middle between high and low uncertainty.

The parameters α, β of the beta distribution are calculated from the following well known (e.g. Rausand et al., 2004) facts for the mode, which equals the assessed most likely score, s and standard deviation σ,

$$s = \frac{\alpha - 1}{\alpha + \beta - 2}$$

$$\sigma = \sqrt{\frac{\alpha\beta}{(\alpha + \beta)^2(\alpha + \beta + 1)}}$$

In the case when the score is at the boundary of the range of possible scores, the appropriate parameter is set to 1, and the other parameter is calculated from the equation for the standard deviation σ.

Table 6. *Uncertainty representations of scorings.*

Uncertainty category	Range	Standard deviation
Low	-10 to +10	0.91
	-10 to 0; 0 to +10	0.46
Medium	-10 to +10	1.37
	-10 to 0; 0 to +10	0.68
High	-10 to +10	1.82
	-10 to 0; 0 to +10	0.91

An example of beta distributions reflecting high and low uncertainty for the same score (+2) is shown in Figure 5.

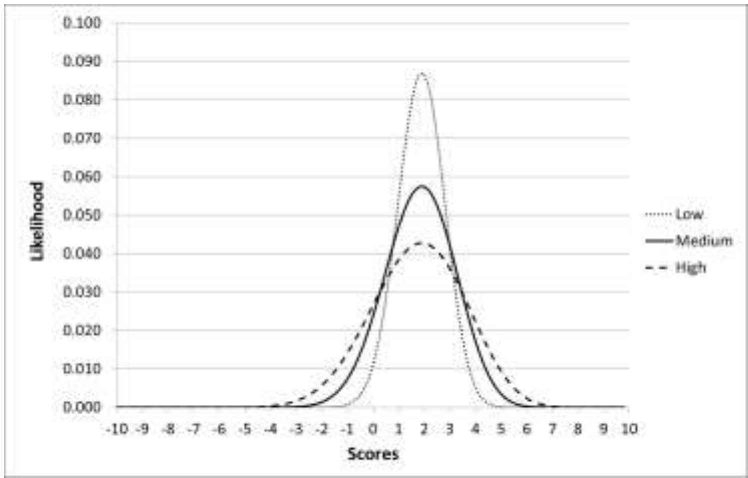


Figure 5. *Uncertainty distributions (beta) for a most likely score of +2 with all scores possible (-10 to +10). Low uncertainty (standard deviation = 0.91), medium uncertainty (standard deviation = 1.37) and high uncertainty (standard deviation = 1.82).*

The assignment of the uncertainty distribution for costs and benefits is performed in two steps. A user of SCORE is supposed to (1) provide the most likely value (*MLV*) of the present value (*PV*) of each of the cost and benefit items and (2) to assign the uncertainty level of the estimation of the *MLV* by choosing one of three different levels of uncertainty: high, medium or low. The procedure results in a log-normal distribution representing the uncertainty of the particular cost or benefit item.

Since a *PV* assigned in SCORE is regarded as being the most probable, it is the mode of the uncertainty density. We have chosen to let the three standard levels of uncertainty – high, medium and low – correspond to the error factors $\sqrt{10} \approx 3.16$, 2 and 1.25, respectively. Note that the UCL (Upper Credibility Limit or largest reasonable *PV*) equals $m\varepsilon$, where m denotes the median and ε the error factor, while the LCL (Lower Credibility Limit or lowest reasonable *PV*) equals m/ε (Rausand et al., 2004). Thus, the ratios $\frac{UCL}{LCL} = \varepsilon^2$ are 10, 4 and 1.5625 for the three levels of uncertainty. Denote by μ and σ the mean and standard deviation on the log scale of the uncertainty distribution for a net present value, then

$$\sigma = \frac{\log \varepsilon}{z_\alpha}$$

and

$$\mu = \log MLV + \sigma^2$$

where z_α denotes the standard normal quantile corresponding to the risk α. Note also that

$$m = e^\mu$$

These facts follow readily from well-known properties of the lognormal distribution. Our final choice is to let $\alpha = 0.05$. Thus the credibility (or certainty) of the interval between LCL and UCL is 90%.

Table 6 illustrates the relative size of this interval for the high, medium and low level of uncertainty. The 90 % credibility interval is also indicated in Figure 6 for the three levels of uncertainties given a mode value of *PV* equal to unity.

Table 6. *The relative size of the 90 % credibility interval for the three standard uncertainty levels of cost and benefit items. For example, the credibility interval ranges from 0.60MLV to 2.39MLV for medium uncertainty.*

Uncertainty category	**LCL/MLV**	**UCL/MLV**
High	0.52	5.16
Medium	0.60	2.39
Low	0.81	1.27

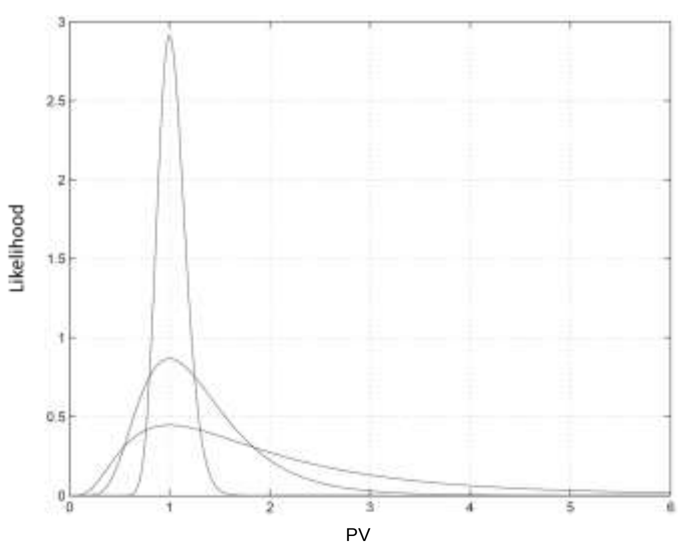


Figure 6. *Log-normal uncertainty distributions for three levels of uncertainty for a MLV = 1.*

3. EXAMPLE

SCORE has been tested at four sites in Sweden and Austria; The Hexion former chemical industry in Mölndal, Sweden; the Marieberg former wood preservation plant in Kramfors, Sweden; Limhamn former cement manufacturing plant in Malmö, Sweden; and a former shooting range in Linz, Austria. The Hexion case study is shown here to illustrate a practical application of SCORE.

The Hexion site

The Hexion site is located in the Gothenburg area of south-western Sweden and has a long history of production of paint and various types of binding agents. An overview of the site is shown in Figure 7.

Figure 7. *Aerial photo over the Hexion site. The white line marks the border of the site and the dotted line marks the river Mölndalsån (from Landström and Östlund, 2011). Photo: National Land Survey of Sweden, Gävle, Sweden.*

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 with school and preschool, shops and offices, traffic areas and parking lots, and green areas with playing grounds. Due to its location 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 have to be removed.

Remediation alternatives

Four remediation alternatives were identified (Table 7), 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.

A SCORE assessment was performed on the four alternatives against a reference alternative, defined as the site is left without remediation and with a closed chemical 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, together with assessments of air emissions and use of non-renewable natural resources. Soil function assessment was performed using the approach described by Volchko et al. (2014). Social scorings were primarily based on interviews with representatives from the environmental controlling authority and the company exploiting the site, the latter which had carried out interviews with neighbours to the site. A detailed CBA was performed in cooperation with project managers and local city representatives.

Alternative 1 represents remediation by excavation and disposal of all contaminated soil with concentrations above the generic guideline values for “sensitive land use” according to Swedish EPA (2009b). Alternatives 2-4 represent remediation of all contaminated soil with concentrations above guideline values based on a site specific risk assessment, taking into consideration the expected exposure conditions and environmental protection values at the site (Sweco, 2009). Alternative 2 represents excavation and disposal of all contaminated soil with concentrations above the site-specific guideline values, whereas alternatives 3 and 4 represent excavation of all contaminated soil with concentrations above the site-specific guideline values combined with on-site pre-treatment and re-use of cleaned soil before disposal of remaining contaminated soil.

Table 7. Remediation alternatives at the case study site

Alternative 1	Alternative 2	Alternative 3	Alternative 4
Excavation and disposal based on a simplified (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.

To illustrate the use of SCORE for reflecting the wide range of applicability and different preferences with respect to the relative importance of sustainability domains and the economic analysis three different scenarios are shown: Scenario A; giving sustainability domains equal weights and performing a full CBA; Scenario B: giving sustainability domains different weights and performing a full CBA; and Scenario C: giving sustainability domains equal weight but including only the cost side in the economic assessment, i.e. performing a CEA.

Inputs to the SCORE assessment

Table 8, Table 9 and Table 10 show the input values for the four alternatives for the environmental, social and economic domains. The weights of the criteria in the environmental and social domain are shown in Figure 8.

Table 8. *Input values for the Hexion site in the environmental domain. NR = Not relevant; NP = No positive scores possible; NN = No negative scores possible; AS = All scores possible; Mode = most likely score; Unc = degree of uncertainty.*

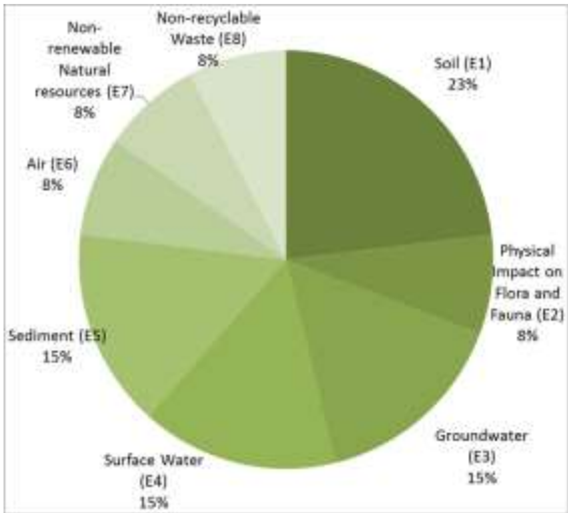
Key criteria	Sub-criteria	Alternative 1			Alternative 2			Alternative 3			Alternative 4		
		Range	Mode	Unc	Range	Mode	Unc	Range	Mode	Unc	Range	Mode	Unc
E1: Soil	Ecotoxicological risk RA On-site	NP	-2	L	NP	0	H	NP	0	H	NP	0	M
	Ecotoxicological risk SC On-Site	NN	4	M	NN	4	M	NN	4	M	NN	4	M
	Soil Functions RA On-Site	AS	4	M	AS	4	M	AS	4	M	AS	4	M
E2: Physical Impact on Flora and fauna	Flora and fauna RA On-Site	AS	0	M	AS	0	M	AS	0	M	AS	0	M
E3: Groundwater	Groundwater RA On-Site	AS	0	M	AS	0	M	AS	0	M	AS	0	M
	Groundwater RA Off-Site	NR			NR			NR			NR		
	Groundwater SC On-Site	AS	8	M	AS	4	M	AS	4	M	AS	4	M
	Groundwater SC Off-Site	NR			NR			NR			NR		
E4: Surface Water	Surface Water RA On-Site	NR			NR			NR			NR		
	Surface Water RA Off-Site	NP	0	M	NP	0	M	NP	0	M	NP	0	M
	Surface Water SC On-Site	NR			NR			NR			NR		
	Surface Water SC Off-Site	NN	0	L	NN	0	L	NN	0	L	NN	0	M
E5: Sediment	Sediment RA On-Site	NR			NR			NR			NR		
	Sediment RA Off-Site	NP	0	M	NP	0	M	NP	0	M	NP	0	M
	Sediment SC On-Site	NR			NR			NR			NR		
	Sediment SC Off-Site	NN	0	L	NN	0	L	NN	0	L	NN	0	L
E6: Air	Air RA Off-Site	NP	-9	L	NP	-6	M	NP	-5	M	NP	-5	M
E7: Non-renewable Natural resources	Natural Resources RA Off-Site	NP	-9	L	NP	-5	L	NP	-2	M	NP	-1	M
E8: Non-recyclable Waste Generation	Waste RA Off-Site	AS	-9	M	AS	-5	M	AS	-2	M	AS	-1	M

Table 9. *Input values for the Hexion site in the social domain. NP = No positive scores possible; NN = No negative scores possible; AS = All scores possible; Mode = most likely score; Unc = degree of uncertainty; L = Low uncertainty; M = Medium uncertainty; H = High uncertainty.*

Key criteria	Sub-criteria	Alternative 1			Alternative 2			Alternative 3			Alternative 4		
		Range	Mode	Unc	Range	Mode	Unc	Range	Mode	Unc	Range	Mode	Unc
S1: Local Environmental Quality and Amenity (LEQ)	LEQ RA On-Site	NR			NR			NR			NR		
	LEQ RA Off-Site	AS	-5	M	AS	-4	M	AS	-3	M	AS	-2	M
	LEQ SC On-Site	AS	8	L	AS	8	L	AS	8	L	AS	8	L
	LEQ SC Off-Site	AS	4	M	AS	4	M	AS	4	M	AS	4	M
S2: Cultural Heritage	Cultural Heritage RA On-Site	NP	-1	L	NP	-1	L	NP	-1	L	NP	-1	L
	Cultural Heritage RA Off-Site	AS	0	L	AS	0	L	AS	0	L	AS	0	L
S3: Health and Safety	Health and Safety RA On-Site	AS	-4	M	AS	-3	M	AS	-4	M	AS	-4	M
	Health and Safety RA Off-Site	AS	-4	M	AS	-3	M	AS	-2	M	AS	-1	M
	Health and Safety SC On-Site	AS	0	L	AS	0	L	AS	0	L	AS	0	L
	Health and Safety SC Off-Site	AS	8	M	AS	8	M	AS	8	M	AS	8	M
S4: Equity	Equity RA On-Site	NR			NR			NR			NR		
	Equity RA Off-Site	AS	-2	M	AS	-2	M	AS	-2	M	AS	-2	M
	Equity SC On-Site	NN	8	M	NN	6	M	NN	6	M	NN	6	M
	Equity SC Off-Site	NN	8	M	NN	6	M	NN	6	M	NN	6	M
S5: Local Participation	Local Participation RA On-Site	AS	0	M	AS	0	M	AS	0	M	NN	0	M
	Local Participation RA Off-Site	NN	4	M	NN	4	M	NN	4	M	NN	4	M
	Local Participation SC On-Site	NN	8	M	NN	8	M	NN	8	M	NN	8	M
	Local Participation SC On-Site	NN	4	M	NN	4	M	NN	4	M	NN	4	M
S6: Local Acceptance	Local Acceptance RA On-Site	NR			NR			NR			NR		
	Local Acceptance RA Off-Site	NN	4	M	NN	6	M	NN	7	M	NN	8	M
	Local Acceptance SC On-Site	NR			NR			NR			NR		
	Local Acceptance SC On-Site	NN	8	M	NN	8	M	NN	8	M	NN	8	M

Table 10. *Input values for the CBA of Hexion remediation alternatives. All monetary values in million Swedish kronor (MSEK). P = Payer; B = Beneficiary; DEV = Developer; EMP = Employees; PUB = Public, including neighbors; NR = Not relevant; (X) = Non-monetized item judged to be somewhat important; X = Non-monetized item judged to be very important; Unc = degree of uncertainty; L = Low uncertainty; M = Medium uncertainty; H = High uncertainty.*

Main items	Sub-items	Alternative 1			Alternative 2			Alternative 3			Alternative 4		
		B/P	Mode	Unc	B/P	Mode	Unc	B/P	Mode	Unc	B/P	Mode	Unc
B1. Increased property values	B1. Increased property value on site	DEV	48.81	M	DEV	48.81	M	DEV	48.81	M	DEV	48.81	M
B2. Improved Health	B2a. Reduced acute health risks	NR			NR			NR			NR		
	B2b. Reduced non-acute health risks	EMP	0.0003	M	EMP	0.0003	M	EMP	0.0003	M	EMP	0.0003	M
	B2c. Other types of improved health, e.g. reduced anxiety	PUB	0.07	M	PUB	0.07	M	PUB	0.07	M	PUB	0.07	M
B3. Increased provision of ecosystem services	B3a. Increased recreational opportunities on site	PUB	X		PUB	X		PUB	X		PUB	X	
	B3b. Increased recreational opportunities in the surroundings	PUB	(X)		PUB	(X)		PUB	(X)		PUB	(X)	
	B3c. Increased provision of other ecosystem services	PUB	(X)		PUB	(X)		PUB	(X)		PUB	(X)	
B4. Other positive externalities	B4. Other positive externalities	NR			NR			NR			NR		
C1. Remediation costs	C1a. Costs for investigations and design of remedial actions	NR			NR			NR			NR		
	C1b. Costs for contracting	NR			NR			NR			NR		
	C1c. Capital costs due to allocation of funds to the remedial action	DEV	1.18	M	DEV	0.78	M	DEV	0.77	M	DEV	0.95	M
	C1d. Costs for the remedial action, including possible transport and disposal of contaminated soil minus possible revenues of reuse of contaminants and/or soil	DEV	38.9	M	DEV	25.87	M	DEV	25.52	M	DEV	31.4	M
	C1e. Costs for design and implementation of monitoring programs including sampling, analysis and data processing	DEV	9.32	M	DEV	9.32	M	DEV	9.32	M	DEV	9.32	M
	C1f. Project risks	DEV	4.56	M	DEV	2.41	L	DEV	1.7	L	DEV	1.65	M
C2. Impaired health due to the remedial action	C2a. Increased health risks due to the remedial action on site	DEV	0.84	M	DEV	0.84	M	DEV	0.84	M	DEV	0.84	M
	C2b. Increased health risks due to transports to and from the remediation site	DEV	1.52	M	DEV	0.9	M	DEV	0.77	M	DEV	0.64	M
	C2c. Increased health risks at disposal sites	NR			NR			NR			NR		
	C2d. Other types of impaired health due to the remedial action, e.g. increased anxiety	PUB	(X)		PUB	(X)		PUB	(X)		PUB	(X)	
C3. Decreased provision of ecosystem services on site	C3a. Decreased provision of ecosystem services on site due to the remedial action	PUB	(X)		PUB	(X)		PUB	(X)		PUB	(X)	
	C3b. Decreased provision of ecosystem services off site due to the remedial action	PUB	0.56	M	PUB	0.35	M	PUB	0.33	M	PUB	0.31	M
	C3c. Decreased provision of ecosystem services due to environmental effects at the disposal site	PUB	(X)		PUB	(X)		PUB	(X)		PUB	(X)	
C4. Other negative externalities	C4. Other negative externalities	NR			NR			NR			NR		



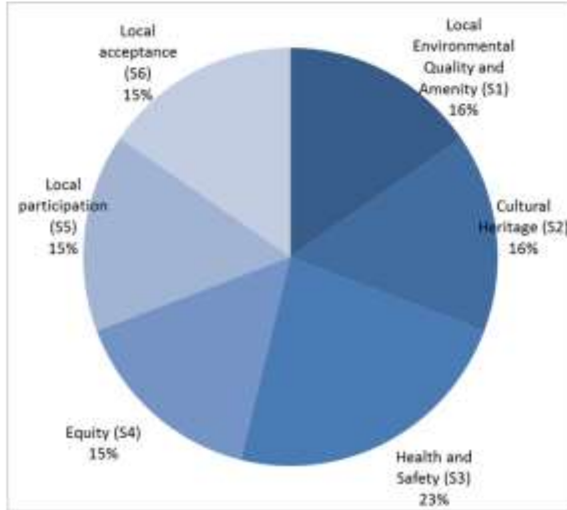


Figure 8. *Weights of criteria in the environmental (left) and social domains (right).*

Results

Figure 9 shows parts of the SCORE results for Scenario A with all domains given equal weight and a full CBA. All alternatives performed well in the social domain. Alternative 1, associated with the most extensive excavation and disposal, had a positive scoring in the social domain, but a negative environmental scoring due to substantial waste generation, air emissions and use of non-renewable natural resources. Alternative 1 also shows the most negative economic outcome due to the extensive excavation work and high costs for transports and disposal. The alternatives based on a site-specific risk assessment (2, 3 and 4) performed better than alternative 1 in the environmental domain, due to less negative impacts from air emissions, use of non-renewable natural resources and waste generation. However, it should be noted that all alternatives were associated with some negative environmental impacts due to waste generation, air emissions and use of non-renewable natural resources. Alternatives based on the site-specific risk assessment also performed considerably better in the economic domain, mainly due to the substantially smaller amount of transports and soil volumes needed to be disposed of. 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). In total, alternatives 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 have compensation between positive and negative effects, i.e. weak sustainability.

The SCORE assessment of the four remediation alternatives was performed using 10,000 Monte Carlo runs. Uncertainty analyses can be provided for all major outputs from SCORE. The uncertainties of the normalized total scores are shown in Figure 10 showing that the assessments for all alternatives are associated with substantial uncertainties. Sensitivity analysis for Alternative 4, which had the highest normalized total score, showed that the property value increase and the remediation costs contributed most to the total uncertainty, see Figure 11. Alternatives 3 and 4 show the highest probabilities of being the most sustainable alternative see Figure 12. All alternatives show more positive than negative effects and most negative effects are off-site, see Figure 13.

To reflect a preference for unequal importance of sustainability domains, Scenario B was performed using an alternative set of weights (*W*) for the sustainability domains; W_E = 50 %; W_S = 33 %; W_{NPV} = 17 %. Finally Scenario C was run with equal weight to domains, but with a CEA approach to the economic assessment, i.e. no quantification of benefits. A summary of the results for Scenarios A, B and C is given in Figure 14.

Scenario B, putting more weight on the environmental effects and less weight on economic effects, resulted in similar results as for Scenario A. The strong environmental performance of Alternative 4 resulted in a higher total sustainability score in Scenario B, ranking somewhat more clearly as the best alternative in Scenario B compared to Scenario A. Scenario C, with a CEA approach to the economic assessment resulted in significantly lower normalized total sustainability indices, since the benefits of the economic assessment were not included in the assessment. However, the ranking of alternatives were the same as for Scenarios A and B. It should be noted that even though no monetary benefits were considered, Alternatives 3 and 4 still had a high probability of a positive normalized total sustainability index, i.e. more positive effects than negative, due to their strong performance in the environmental and social domains.

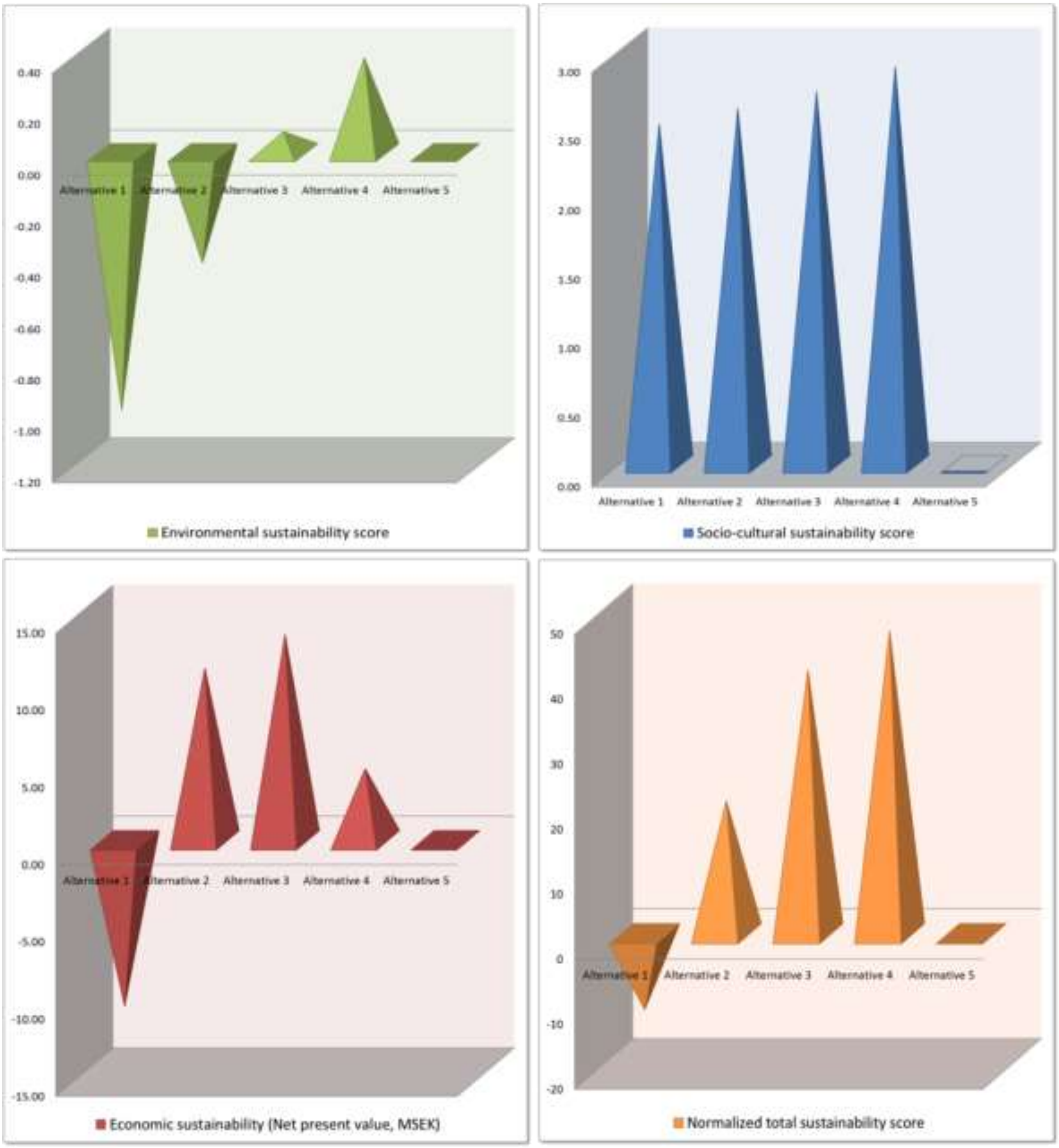


Figure 9. *SCORE results for Scenario A - Environmental sustainability score (upper left), Social sustainability score (upper right), Economic sustainability (lower left), and Normalized total sustainability score (lower right).*

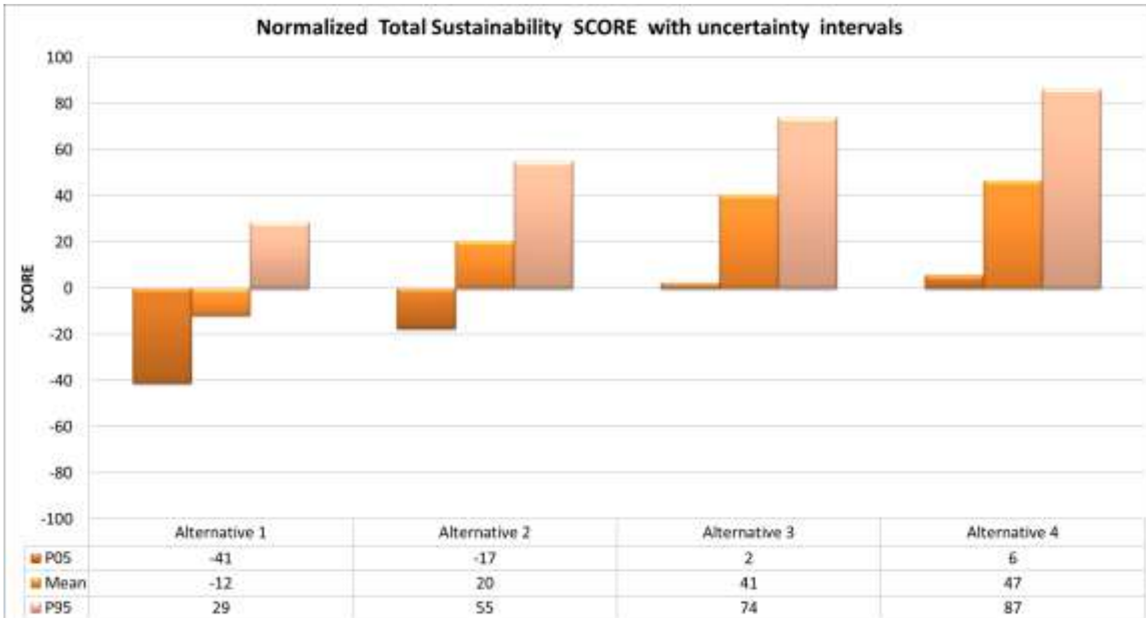


Figure 10. *Normalized total sustainability scores and uncertainties.*

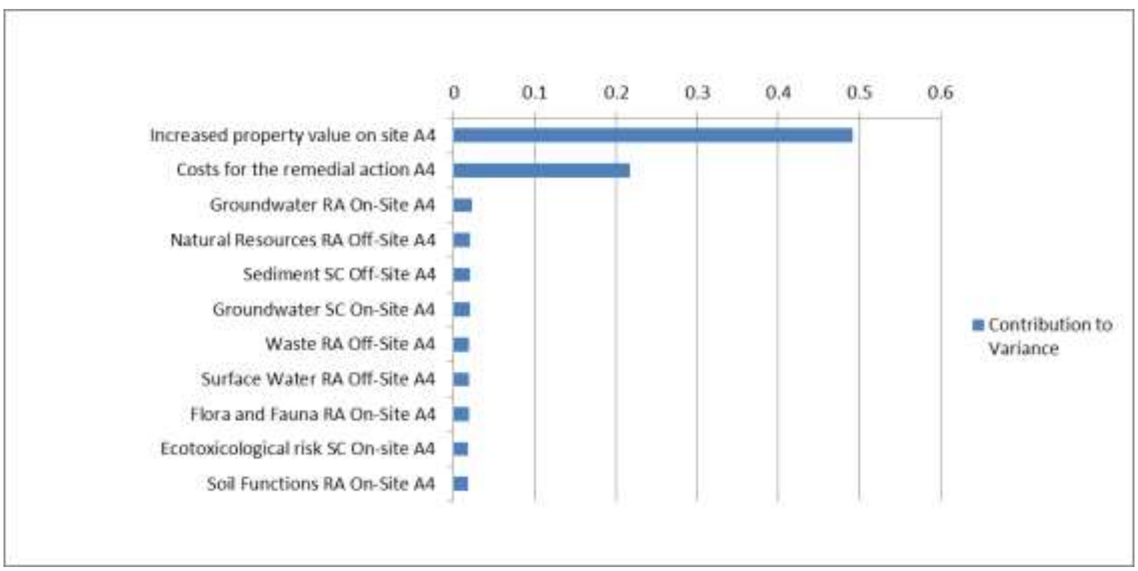


Figure 11. *Sensitivity analysis for Alternative 4. Results expressed as the contribution to the total variance of the normalized sustainability score for Alternative 4.*

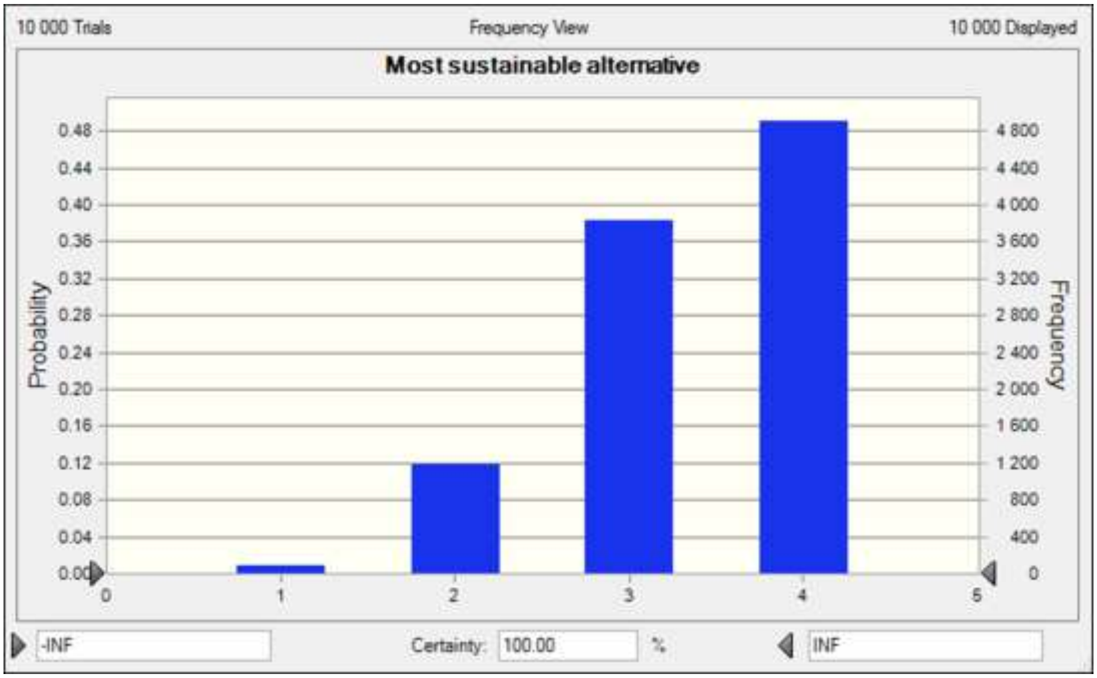
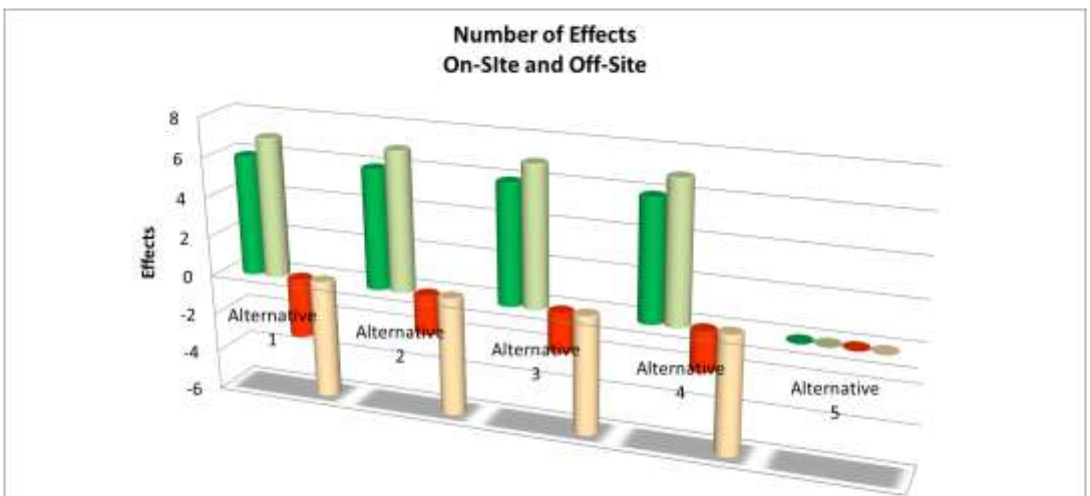


Figure 12. *Probabilities of each alternative being the most sustainable.*



	Alternative 1	Alternative 2	Alternative 3	Alternative 4	Alternative 5
On-Site Positive	6	6	6	6	0
Off-Site Positive	7	7	7	7	0
On Site Negative	-3	-2	-2	-2	0
Off-Site Negative	-6	-6	-6	-6	0

Figure 13. *Number of expected positive and negative effects on-site and off-site, due to the remedial remediation at Hexion.*

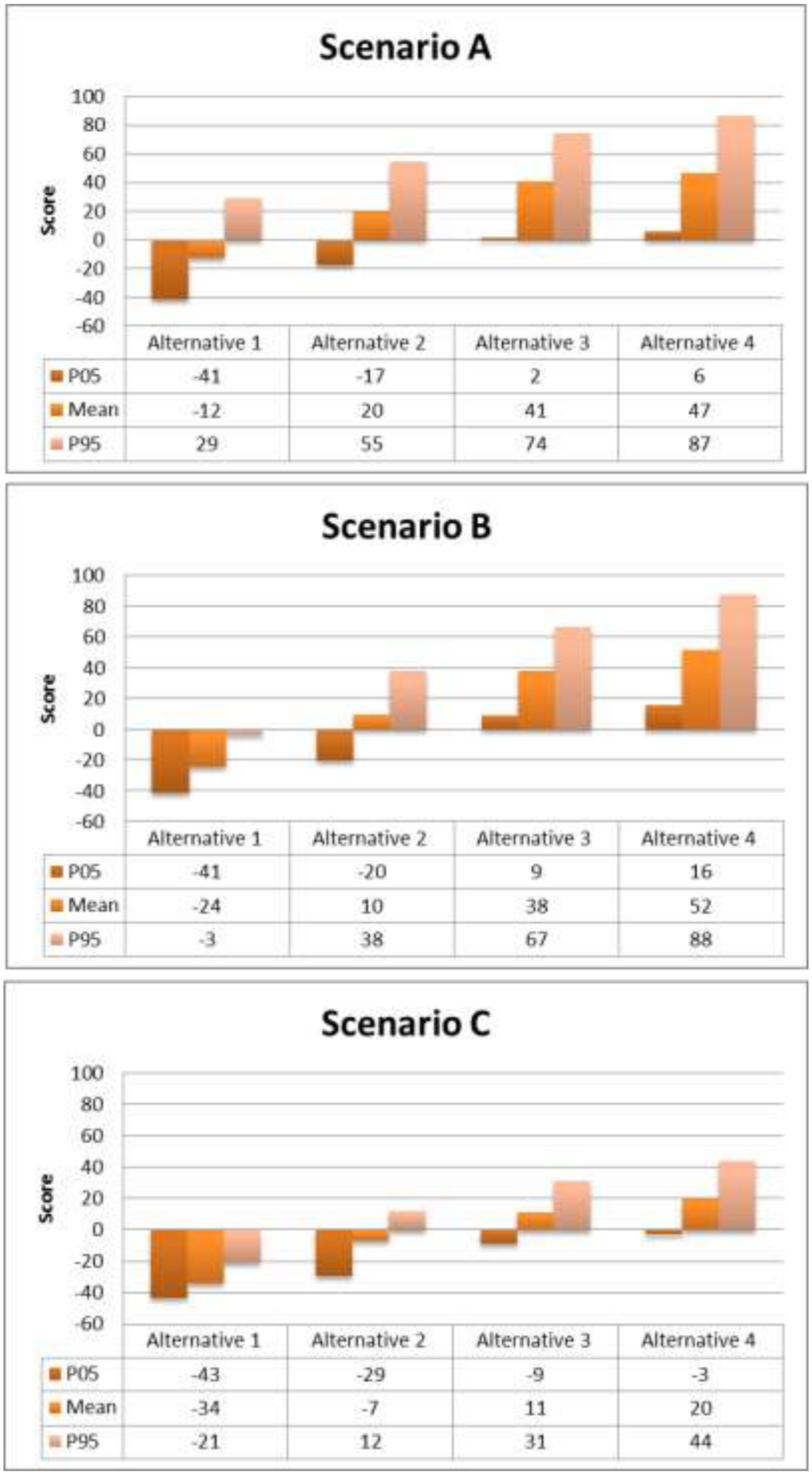


Figure 14. *Normalized total sustainability index with uncertainty intervals for three alternative assessment scenarios.*

4. DISCUSSION AND CONCLUDING REMARKS

Sustainability assessments of remediation are inherently complex and typically involve a large amount of information of very different character, such as hard data from site investigations, environmental footprint analyses, and economic analyses, as well as information reflecting views and preferences among involved stakeholders. Integration of such diverse information to support decisions on sustainable remediation and sound prioritization of society's limited resources requires a clear structure and reliable assessment tools. It also requires that organizations among problem-owners, authorities, consultants, contractors, and others are willing to accept a holistic view on site remediation. A major challenge in making remediation sustainable is transfer of knowledge to involved groups and decision-makers. This transfer is likely to be facilitated by methods, such as SCORE, that can be practically applied and readily used to gain experience and show real-world examples.

SCORE provides: (1) structure, transparency and decision support for identifying sustainable remediation alternatives and for improving 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 ecosystem services; (4) a means for including effects on soil functions and soil services in accordance with future EU regulations regarding soil; (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; (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 assessments, and (7) a structure for displaying and investigating the impacts and sensitivity of different views and preferences among involved stakeholders.

The SCORE method has been implemented in a computer tool (in Excel), which facilitates practical application. However, as with all models and tools, SCORE produces results given the chosen boundary conditions, the selection of model parameters, and the inputs used. The users of SCORE (as with any other model) thus have a responsibility not to use SCORE as a black box model and to carefully familiarize with concepts and boundary conditions of the method. The SCORE tool has been designed with this in mind to serve as a decision support tool, providing a clear and informative description of the method and its boundaries, together with guides and examples to illustrate the practical use of SCORE.

The objective of the SCORE project was to develop a transparent method, where different views and preferences of involved stakeholders can be reflected, e.g. by scenario analysis as shown earlier in the example. However, it should be noted that SCORE currently does not provide any guidance on *how* stakeholders should be involved in the assessment process. To produce acceptable results using SCORE, stakeholders should be engaged throughout the process: defining the alternatives to be assessed, selection and weighting of criteria and collection of information and discussions to base the scoring on.

SCORE can be used for remediation projects of different scales, but the required information is more often found in larger remediation projects. Information on environmental effects is typically available from e.g. site investigations, risk assessments, and foot print analyses. Economic (at least concerning externalities relating to health, safety, and ecosystem services) and social information may be lacking in already performed remediation projects (see e.g. Rosén et al., 2014), but is becoming more readily available in ongoing or planned projects as the interest in sustainable remediation increases.

SCORE has been successfully applied on four remediation projects, differencing in location (Sweden and Austria), setting (urban and rural), type of pollutants, area of concerns (soil, groundwater, surface water, etc), and liability. However, further applications are needed in order to be able to fully evaluate the applicability of the method to different types of remediation projects, e.g. exploitation projects in urban areas, projects in rural locations with very low demand on land, and projects where remediation is initiated by liability and regulatory issues. Applications in on-going remediation projects are planned for 2014-2017, which will form a basis for evaluation of the applicability on different types of projects and needed adjustments of the method.

SCORE is based on what we, based on current knowledge, consider to be the most relevant key criteria, but structured in a way that allows for different views of sustainability (e.g. Figure 1). The SCORE framework is at its core designed to be flexible and transparent, making it possible to account for alternative and upcoming perspectives on sustainability. SCORE will be further developed to better handle missing information (e.g. to account for smaller remediation projects) and future-proofing core modules for even more flexibility and adaptability.

Finally, it should be noted that 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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