THESIS FOR THE DEGREE OF LICENTIATE OF ENGINEERING

Investigating the Relation between Efficient, Effective and Sustainable Remediation of Contaminated Sites

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ABSTRACT

Remediation of contaminated sites reduces negative impacts to humans and the environment, but the process itself is typically associated with high costs to society and large environmental footprints. The sustainable remediation concept has, over the past decade, brought increased attention to the often-overlooked contradictory effects of site remediation. At the same time, the Swedish Environmental Protection Agency (SEPA) is concerned over the slow progress of publicly funded projects, calling for more efficient and effective remediation. The aim of this thesis is to investigate the impact of a sustainability view on the efficiency and effectiveness of contaminated site remediation. How efficiency and effectiveness are considered in literature with respect to contaminated sites was studied. The contribution of a sustainability view on the selection of remedial actions was demonstrated through scenario analysis (Paper I). This involved using the SCORE sustainability assessment method to analyze four real case study sites in Sweden. Remediation alternatives at the same four case studies were assessed based on project efficiency and effectiveness indicators found from literature and group interviews (Paper II). Sustainability assessment, considering broader environmental effects, soft social aspects, and economic externalities, can result in a decision support outcome which differs compared with more limited assessment approaches, typically balancing trade-offs such as the extent of remediation with negative secondary effects such as emissions. The studied effectiveness and efficiency indicators, pertaining primarily to time, costs, and amounts removed, generally favour the most extensive and low-cost alternatives, respectively. The indicators are not seen to strongly support the most sustainable alternatives, however a full sustainability view likely leads to less extensive and expensive remediation projects compared to a traditional assessment approach.

Keywords: contaminated sites, sustainability assessment, decision support, multi-criteria decision analysis, cost-benefit analysis, efficient remediation, effective remediation

LIST OF PAPERS

This thesis includes the following papers, referred to by Roman numerals:

I. Anderson, R., Norrman, J., Back, P.-E., Söderqvist, T. & Rosén, L. (2018). What's the point? The contribution of a sustainability view in contaminated site remediation. *Science of the Total Environment*, *630*, 103-116.

II. Anderson, R., Norrman, J., Söderqvist, T. & Rosén, L. (2018). Assessing efficiency and effectiveness of remediation alternatives at contaminated sites. Manuscript.

Division of work between authors

In Paper I, all authors contributed to the design of the study. Anderson performed the work and simulations in the SCORE tool and was the main author. Writing and analysis was performed primarily by Anderson and Norrman, with key input from Rosén. Back and Söderqvist provided important comments and review of the paper.

In Paper II, all authors contributed to the design of the study. Anderson performed the work in finding and presenting the data and was the main author. Writing and analysis was mainly done by Anderson and Norrman, with key contribution from Rosén and Söderqvist.

Other work and publications not appended

III. Volchko, Y., Rosén, L., Norrman, J., Bergknut, M., Gernot, D., Anderson, R., Tysklind, M. & Müller-Grabherr, D. (2014). *SNOWMAN - MCA: Multi-criteria analysis of remediation alternatives to access their overall impact and cost/benefit, with focus on soil function (ecosystem services and goods) and sustainability*. Report 2014:6. Department of Civil and Environmental Engineering, Chalmers University of Technology, Gothenburg, Sweden.

IV. Anderson, R., Norrman, J., Rosén, L., Volchko, Y., Söderqvist, T. & Franzén, F. (2016). *What is efficient remediation and how can it be measured*? *(Abstract)*, Oral Presentation at 4th International Conference on Sustainable Remediation (SustRem), Montréal, April 26-28.

V. Anderson, R., Norrman, J., Rosén, L. & Volchko, Y. (2016*). Is Sustainable Remediation of Contaminated Land More Efficient? (Abstract)*, Poster at the Society for Risk Analysis Annual Meeting, San Diego, December 11-15.

VI. Anderson, R. (2017). *Efficient Remediation of Contaminated Sites: A Literature Review*. Report. Department of Architecture and Civil Engineering, Chalmers University of Technology, Gothenburg, Sweden.

VII. Brinkhoff, P., Garção, R., Anderson, R., Norin, M., Janmar, L., Norrman, J. & Volchko, Y. (2018). *SCORE assessment at Limhamns läge in Malmö municipality – Case study report*. Report. Department of Architecture and Civil Engineering, Chalmers University of Technology, Gothenburg, Sweden. To be published in 2018.

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Gothenburg, May 2018

Robert Anderson

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LIST OF NOTATIONS

The following notations are used in the main text of the thesis:

CBA	Cost-Benefit Analysis
CEA	Cost-Effectiveness Analysis
CLM	Contaminated Land Management
DST	Decision Support Tool
FCSAP	Federal Contaminated Sites Action Plan
ISO	International Organization for Standardization
LCA	Life Cycle Assessment
LCL	Lower Credibility Limit
MCDA	Multi-Criteria Decision Analysis
MIFO	Method for Surveying Contaminated Sites
MLV	Most Likely Value
NICOLE	Network for Industrially Co-ordinated Sustainable Land Management in Europe
NPV	Net Present Value
PV	Present Value
RA	Remedial Action
SAFIRE	Sustainability Assessment for Improved Remediation Efficiency
SC	Source Contamination
SCORE	Sustainable Choice Of REmediation
SEPA	Swedish Environmental Protection Agency (Naturvårdsverket)
SGI	Swedish Geotechnical Institute
SGU	Swedish Geological Survey
SURF	Sustainable Remediation Forum
TUFFO	Teknikutveckling och Forskning inom Förorenade Områden
UCL	Upper Credibility Limit
US EPA	United States Environmental Protection Agency

1 INTRODUCTION

This chapter provides a background to the doctoral project. The aim, objectives and scope of the work are presented, along with the limitations of the thesis.

1.1 Background

Contamination of land and water resources, posing risks to humans and ecosystems, places a large burden on society. The Swedish Environmental Protection Agency (SEPA), the national authority dealing with contaminated sites, has estimated that there are 80,000 potentially contaminated sites in Sweden (SEPA, 2014). 8000 sites[1] have been inventoried by the Swedish EPA as high risk sites (SEPA, 2017). The situation is similar in many other industrialized countries worldwide, with an estimated 2.5 million potentially contaminated sites in Europe, and 217,000 in the United States (Panagos et al., 2013; USEPA, 2004).

Public funding is required in order to clean up contaminated sites in cases where there is no legally liable private owner or operator of a site. The Swedish EPA is concerned over the slow progress and high cost of publicly funded remediation projects, and that the national environmental objective related to contaminated sites, *A Non-Toxic Environment*, will not be met in time (SEPA, 2017; SGI, 2015; SEPA, 2012a). The average cost of a publicly funded project in Sweden has been estimated to 40 million SEK[2] (WSP, 2013), and remediation of all high risk sites is not expected to be completed prior to year 2129 (SEPA, 2013a). An “efficiency audit” on the national remediation program has concluded that there are significant shortcomings in the surveying of state responsible sites, making estimation of risks difficult and cost-effective site prioritization complicated (Riksrevisionen, 2016).

In addition to concern over time and costs, the Swedish Geotechnical Institute (SGI), through the TUFFO program, is interested in increasing the level of innovation of remediation projects (SGI, 2018). In particular, there is high interest in reducing the number of projects completing remediation by means of excavation and disposal. This straightforward remediation technique, often called “dig and dump”, is typically extensive in removal of contamination, but at high costs. Additionally, while the technique results in significant reduction of risks to humans and ecosystems, it is associated with contradictory effects, such as substantial emissions, noise and dust on-site, waste production, and use of non-renewable natural resources (Kuppusamy et al., 2016; USEPA 2008a). Excavation and disposal is the most common technique used in Sweden (SEPA, 2006).

Increased awareness of the above mentioned contradictory effects of remediation has been seen in the past decade, giving rise to the “green remediation” and “sustainable remediation”

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[1] Sites in risk classes 1 (very high risk) and 2 (high risk).
[2] 40million Swedish Kronor (SEK) is approximately equal to 4 million €.

concepts. The green remediation concept has been adopted in the US, which focuses mainly on minimizing the negative effects of remediation on the environment; see e.g. USEPA, (2008b), and Hadley and Harclerode (2015). The sustainable remediation concept focuses on implementing solutions leading towards sustainable development, where projects are typically assessed within three dimensions: environmental sustainability, social sustainability, and economic sustainability; see e.g. Bardos et al. (2011), US Sustainable Remediation forum (2009), ISO (2017). Decision support tools (DSTs) of varying type, scope, and purpose, have been developed to aid in the complex decision making process of how best to clean up a site. The SCORE (Sustainable Choice Of Remediation) method and tool, developed at Chalmers, is a multi-criteria decision analysis (MCDA) tool for assessing and ranking sustainability of remediation alternatives at contaminated sites.

The goal of increasing the efficiency and effectiveness of publicly funded remediation in Sweden has been paralleled by the growth of the sustainable remediation concept and a general push for including sustainability aspects in the assessment of remedial actions (SEPA, 2009a). This has therefore led to the question of whether sustainability assessments lead to improved remediation efficiency and effectiveness. In order to answer this main question, however, two additional questions must be asked. The first is: *what constitutes efficient and effective remediation?* i.e. what are the differences between efficient and effective in the context of site remediation, what aspects other than time and costs can and should be considered, and how can these be measured? The second question is: *what is the impact of a sustainability view on the selection of remedial actions?* i.e. how does a full sustainability view compare with traditional and "green" assessment scopes, and differing (private vs. public) perspectives? These questions have guided and structured the work presented in this thesis, as outlined below in the aim, objectives and scope.

1.2 Aim and Objectives

The overall aim of this work is:

> *to investigate the impact of a sustainability view on the efficiency and effectiveness of contaminated site remediation.*

Specific objectives in achieving the aim are:

- To present how remediation efficiency and effectiveness are defined in literature;
- To investigate the contribution of a sustainability view in remediation projects, compared with other assessment views, on decision support outcomes;
- To assess the efficiency and effectiveness of remediation alternatives at contaminated sites.

1.3 Scope

The overall aim of this thesis is attained through the work presented in the publications shown in Figure 1-1 below. An initial literature review was performed to determine possible efficiency and effectiveness indicators to be used for further study (objective 1). In Paper I, a scenario analysis was performed on four case study sites in Sweden, investigating the contribution of a sustainability view in contaminated site remediation (objective 2). In Paper II, remediation alternatives at the same four case studies were studied with respect to the efficiency and effectiveness indicators previously presented (objective 3).

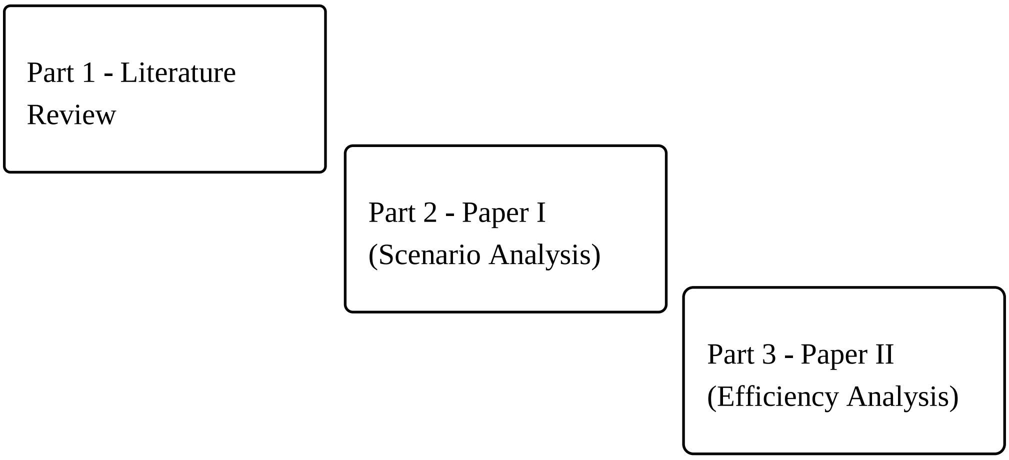

Figure 1-1. Scope of the work.

Included in this thesis is background on the remediation process in Sweden (Section 2) as well as on sustainable remediation and available assessment methods and tools (Section 3). Section 4 presents the SCORE method and the methods used in performing the literature review, scenario analysis, and efficiency and effectiveness analysis. Section 5 presents the four case study sites. Section 6 presents the results of the literature review, Paper I, Paper II, as well as results in combining Paper I and II. Section 7 discusses the results and Section 8 provides the main conclusions of the thesis.

Limitations of the work presented in this thesis includes the following:

- Consideration of efficiency and effectiveness does not include administrative, legal or political aspects;
- The sustainability view studied was limited to the SCORE method and tool;
- Four case studies were chosen to be included;
- Limitations were found within each case study with respect to the amount of data and information gathered;
- In Part 2, four scenarios were developed, though additional scenarios reflecting different scopes and perspectives could have been included;
- The indicator list used in Part 3 is not exhaustive and was limited to those able to be quantified with given data.

2 CONTAMINATED SITES

This chapter gives an introduction to contaminated sites, describes the remediation process in Sweden, and gives background on presently used remediation techniques.

2.1 Introduction to Contaminated Sites

Contaminated sites are areas of land where concentrations of toxic substances in soil and groundwater exceed local or regional background levels, posing risks to people and the environment (SEPA, 1999). Examples of such substances are: heavy metals (e.g. arsenic, lead), petroleum, chemical substances (e.g. dioxins, PCBs, PFAS/PFOS), asbestos, and radioactive material. In Sweden, contaminated sites are often a result of former industrial activity, e.g. chemical plants, sawmills, pulp and paper mills, glass works, mining etc. (SEPA, 2018). Human exposure to soil contamination can occur through a number of exposure pathways, of which the most commonly considered are: dermal contact, intake of soil, drinking water and vegetables grown at the site, and inhalation of vapours and dust. Ecological receptors that are considered in Sweden are the soil ecosystem, the surface water ecosystem and groundwater. Figure 2-1 shows the former Köja sawmill outside of Kramfors, Sweden, shut down in 1940, heavily contaminated with pentachlorophenol and dioxins as part of the wood impregnation process (Golder Associates, 2013).

Figure 2-1. Left: Example of contaminated site. Remnants of the Köja sawmill and the wood impregnation area. Right: Map of the interpolated dioxin levels within the former sawmill area, where the purple area shows the highest concentrations (>1500ng/kg TS) (Golder Associates, 2013).

Identification and inventory of suspected contaminated sites in Sweden is a process primarily performed by the County Administrations (Länsstyrelserna) under guidance of the Swedish EPA. The inventory is performed according to the MIFO method (Method of Surveying Contaminated Sites) (SEPA, 1999) and the prioritization of sites is based on a risk classification scheme, see Table 2-1. The risk classification for a site considers the branch class of a site, based on the toxicity of contaminants typically handled in different branches, and the specific site conditions. Sites in risk classes 1 and 2 are those prioritized for further investigation and potentially for remediation (SEPA, 2016a).

Table 2-1. Swedish EPA risk classification. (SEPA, 2016a)

Risk Class 1	Very high risk
Risk Class 2	High risk
Risk Class 3	Moderate risk
Risk Class 4	Low risk

2.2 The Remediation Process in Sweden

2.2.1 The Swedish Environmental Objectives

The Swedish Parliament (Riksdag) has adopted 16 environmental quality objectives in order to meet the generational goal of handing over to the next generation (year 2020) a society in which the major environmental problems are solved and where problems are not increased outside Swedish borders (SEPA, 2012a). Detailed descriptions of the goals can be found on the environmental objectives website[3]. The main environmental objective linked to contaminated sites, *4. A Non-Toxic Environment*, is defined as follows:

> *"The occurrence of man-made or extracted substances in the environment must not represent a threat to human health or biological diversity. Concentrations of non-naturally occurring substances will be close to zero and their impacts on human health and on ecosystems will be negligible. Concentrations of naturally occurring substances will be close to background levels." (SEPA, 2016b)*

The objective *A Non-Toxic Environment* will not be reached by 2020, as a result of slow progress of contaminated site remediation. The Swedish EPA therefore formulated an overall goal that all sites with very large or large risk to human health and the environment (Risk Class 1 & 2) be remediated by year 2050 (SEPA, 2013a). Under the overall goal, the following stage goals have been proposed:

- At least 25% of sites with very large risk (Risk Class 1) to human health or the environment are remediated by year 2025.
- At least 15% of sites with large risk (Risk Class 2) to human health or the environment are remediated by year 2025.

[3] www.miljomal.se, accessed 22/03/18

- The use of other remediation techniques than excavation and disposal, without pre-treatment of masses is increased by year 2020.

2.2.2 The Swedish Environmental Code (Miljöbalken)

The Swedish Environmental Code (Miljöbalken) came into force January 1st, 1999, replacing 15 previous environmental acts, and acts as a more modern, broad, and stringent legislation. The purpose of the code is to promote sustainable development, ensuring a healthy and sound environment for present and future generations (SEPA, 2016c).

Section 10 of the Swedish Environmental Code deals with contaminated sites, which is based on what is often called the "Polluter Pays Principle". It is stated that the operator, who is presently operating or previously operated a site which is polluted to the extent of posing risk to human or the environment, is liable for investigation and remediation (SEPA, 2012b). A property owner may also be responsible. It can often be problematic to identify who is responsible for a contaminated site and who should pay for investigation and clean up under the supervision of a controlling authority, since the operator may not exist anymore, or there may have been several operators at the same site.

2.2.3 Remediation Tracks

Remediation projects in Sweden are, depending on the situation, initiated by different drivers, and can be classified under one of three "tracks". The investigation and risk assessment processes, as well as the final result of remediation, is the same for all tracks (SEPA, 2012b; SEPA, 2013a; SEPA, 2015).

1. Supervision Track – The property owner or operator has the responsibility not to contaminate. A controlling authority sets requirements for the problem owner to investigate and remediate the site if necessary. An exception is if operation ended prior to 1969.
2. Publicly Funded Track – In cases where there is no legally liable owner or operator, public funding is used for site investigations and eventual remediation of sites that pose an unacceptable risk. This also includes sites where the government is itself responsible but the organisation that contaminated no longer exists.
3. Exploitation Track – In the case of a change in land-use, such as when a former industrial area is transformed to a residential area, risks must be reduced to levels acceptable for the new land-use. This is common in cities where available land is in high demand. Here it is common for construction companies to purchase a contaminated site and take on full responsibility for the contamination, initiating the investigation and carrying out the remediation privately, under supervision of a controlling authority.

2.2.4 Active Parties

The roles and responsibilities of the main parties involved in the remediation process in Sweden are described in Table 2-2 below.

Table 2-2. Active parties in Swedish remediation projects (SEPA 2012b; SEPA, 2013b; SEPA 2015). Adapted from Anderson (2017).

Active Party	Roles and Responsibilities
Swedish Environmental Protection Agency (Naturvårdsverket)	• Coordination, prioritization, and follow-up of remediation work on a national level • Provides guidance to County Administrations and municipalities • Administers grants • Evaluates impact of grants • Reports to the government and the EU • Participates in European and international forum
County Administration (Länsstyrelsen)	• Acts as controlling authority on supervision sites • Gives guidance to municipalities • Overall responsibility on regional level: inventory, investigation, risk-classification, and prioritization of sites • Distribution of grants in their respective region
Municipality (Kommun)	• Acts as responsible party on publicly-funded sites • Also acts as controlling authority on supervision sites when operator voluntarily investigates site • Carries out pre-studies and investigations
Property owner or Operator	• Obligated to notify the controlling authority if contamination is discovered on their property • Responsible for carrying out investigations and remediation work if needed
Swedish Geological Survey (SGU)	• Investigates and remediates sites where the government is itself responsible but the organisation who contaminated no longer exists. • Acts as responsible party on publicly-funded sites where the municipality can not • Cooperation with the Swedish EPA and SGI to achieve national objective
Swedish Geotechnical Institute (SGI)	• Responsible for research, technical development, and knowledge concerning contaminated sites nationally • Expert support on technical questions to the county administrations and municipalities • Cooperation with the Swedish EPA and SGU to achieve national objective

2.2.5 Risk Assessment and Selection of Remediation Alternatives

The Swedish EPA's process of selecting and implementing remediation alternatives, from goal setting and initial investigations to follow-up and completion, is illustrated in Figure 2-2 below. The importance of documentation and communication with stakeholders throughout the process is stressed by the Swedish EPA (SEPA, 2009a). Steps 3 and 4 are explained in more detail below.

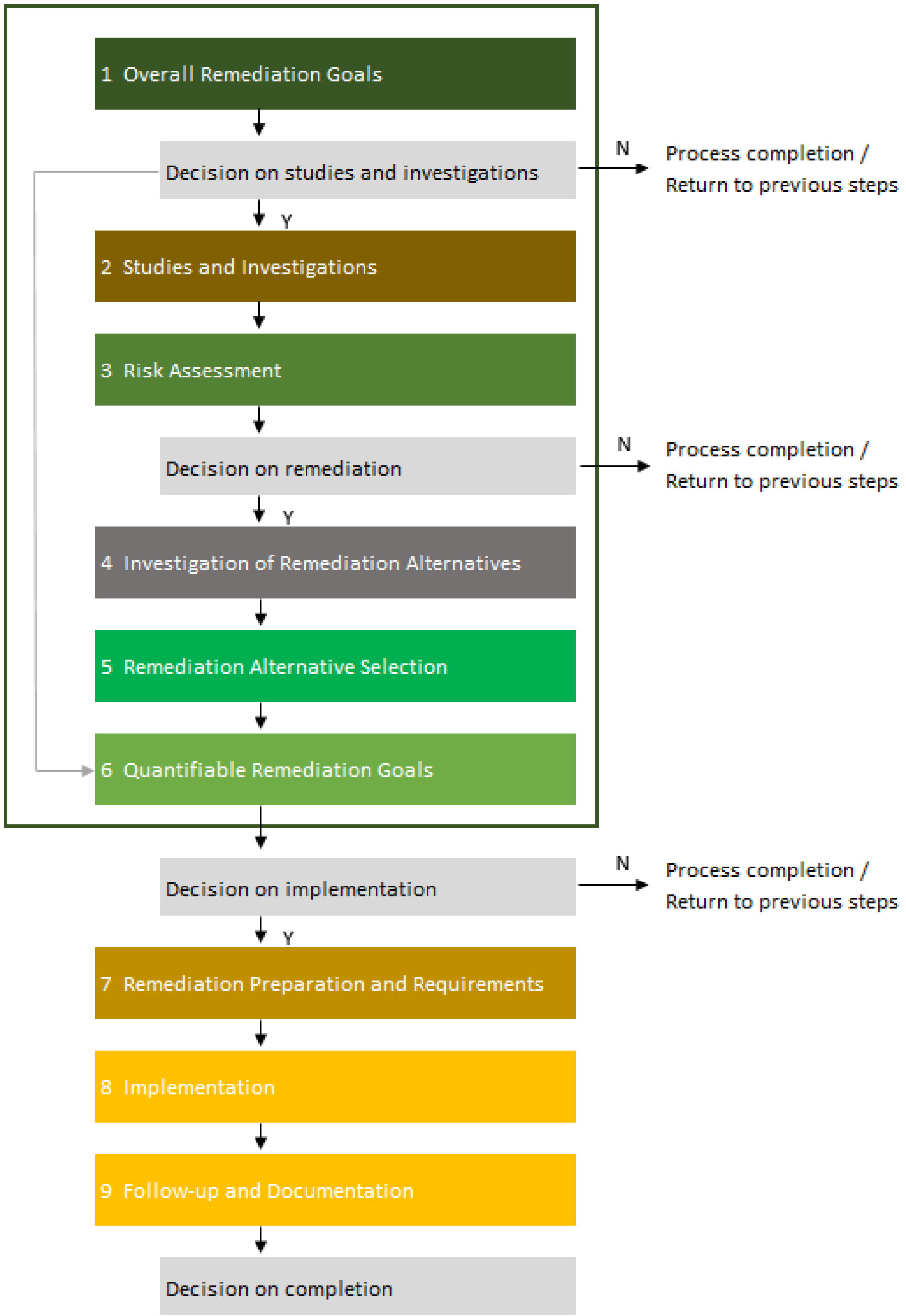

Figure 2-2. Swedish EPA framework for selecting a remediation alternative (within the box). Adapted and translated from Swedish EPA (2009a) and Brinkhoff (2014).

Risk assessment (Step 3) identifies and quantifies the risks that a site poses presently or in the future, and determines if remediation is required and the risk reduction necessary. It also describes potential requirements for remediation such as whether focus is to be placed on the contamination source, transportation and exposure pathways, or recipients (SEPA, 2009b). Risk assessments are based on results of soil sampling and/or water sampling performed in the investigation phase (Step 2). Representative contaminant concentrations from analysis are compared to guideline values or background levels. The Swedish generic guideline values depend on the expected end land-use for the site, classified as either sensitive land use (KM) or less sensitive land use (MKM) (SEPA, 2009c). Exposure and effect analyses are performed in order to characterize the risks at a site. The exposure pathways accounted for in the Swedish EPA risk model for health risks is shown in Figure 2-3. Depending on the complexity of a site and its contamination situation, a more in-depth (tier 2) risk assessment may be required. In the tier 2 analysis, site-specific guideline values are typically developed. Detailed description of the risk assessment step is provided in a guidance report from the Swedish EPA (SEPA, 2009b).

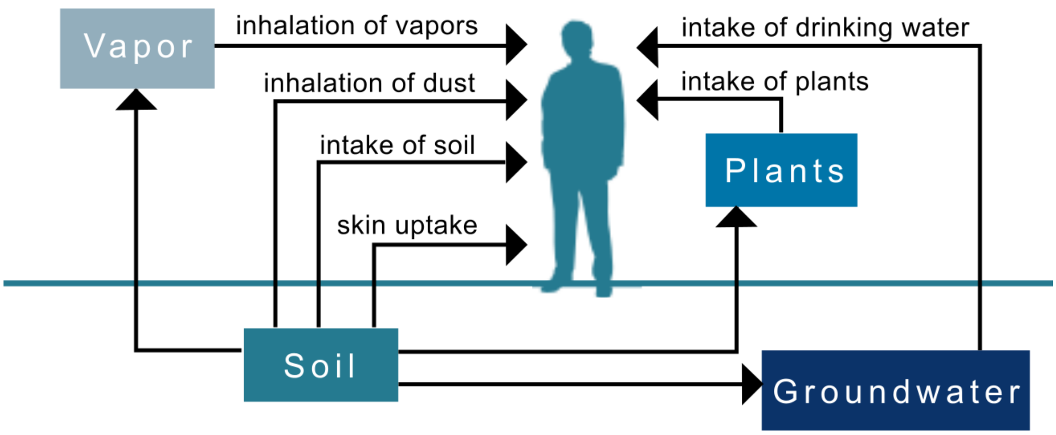

Figure 2-3. Exposure pathways considered in the Swedish EPA human health risk model (adapted and translated from SEPA, 2009c)

Feasibility study and investigation of potential remediation alternatives for a site is performed under Step 4, and is based on the outlined remedial goals (Step 1) and the performed risk assessment (Step 3) (SEPA, 2009a). The feasibility study acts as an important foundation for the selection of an alternative, performed under Step 5. Alternatives are mainly assessed based on expected benefits (risk reduction), costs and technical constraints, though it is recommended that softer aspects are also considered. The assessment of alternatives is meant to be conducted in close contact between the responsible party, the controlling authority, stakeholders and in some cases the public.

2.3 Remediation Techniques

A summary of the most common soil, sediment, and groundwater remediation technologies, divided into in-situ and ex-situ techniques, and by treatment type (physical, chemical, biological, and thermal), is provided in Table 2-3 below (FRTR, 2007). In-situ techniques are those where the contaminated soil stays in place under treatment. Ex-situ techniques are those where the soil is excavated and either treated on-site (e.g. sieving and soil washing, see Figure 2-4), or transported for treatment or disposal elsewhere (Landström & Östlund, 2011). Classification could also be made by whether the technique concentrates the contamination, destroys the contamination, or immobilizes it (SEPA, 2006).

The selection of a remediation technique at a contaminated site depends on different factors such as contamination type, soil type, site characteristics, groundwater level etc. In addition, time, cost and available space can greatly influence the remediation strategy. The Swedish EPA underwent a detailed study in 2006, reviewing the techniques used on 226 projects in Sweden (SEPA, 2006). It was found that the vast majority of the projects used ex-situ excavation and transport and disposal. In-situ vacuum extraction and ventilation was the second most common technique, though it was found that its limited use was due to technical limitations and poor performance of the technique.

Figure 2-4. Excavation and soil sieving at Hexion site in Mölndal, Sweden. Photo: Åsa Landström (Landström & Östlund, 2011)

Table 2-3. Summary of remediation technologies (FRTR, 2007). Adapted from Anderson (2017).

Treatment Type	**In-situ**	**Ex-situ**
Physical	• Fracturing • Soil flushing • Solidification/ Stabilization • Landfill cap/ barriers • Air sparging • Directional wells • Dual phase extraction • In-well air stripping	• Separation • Soil washing • Solidification/ Stabilization • Adsorption/ absorption
Chemical	• Chemical oxidation • Electrokinetic separation • Soil vapor extraction • Passive/ reactive treatment barriers	• Chemical extraction • Chemical reduction/ oxidation • Dehalogenation • Precipitation/ coagulation/ flocculation • Ion exchange
Biological	• Bioventing • Bioslurping • Enhanced Bioremediation • Phytoremediation • Monitored natural attenuation	• Biopiles • Composting • Landfarming • Slurry phase biological treatment • Bioreactors
Thermal	• Thermal treatment	• Hot gas decontamination • Incineration • Open burn/ open detonation • Pyrolysis • Thermal desorption

3 SUSTAINABLE REMEDIATION

This chapter introduces sustainable development, the sustainable remediation concept, and assessment methods and descriptions of available decision support tools for remediation of contaminated sites.

3.1 Sustainable Development

The Brundtland report (Our Common Future), published in 1987 by the World Commission on Environment and Development, helped push the need for sustainable development forward. The commission was initiated by the General Assembly of the United Nations, based on the conflict seen between economic development and environmental preservation, and the first and third-worlds, first acknowledged in the 1970's. The first two paragraphs of the report state:

> *"1. Sustainable development is development that meets the needs of the present without compromising the ability of future generations to meet their own needs. It contains within it two concepts:*
>
> - *the concept of ´needs´, in particular the essential needs of the world's poor, to which overriding priority should be given; and*
> - *the idea of limitations imposed by the state of technology and social organization on the environment's ability to meet present and future needs."*
>
> *2. Thus the goals of economic and social development must be defined in terms of sustainability in all countries – developed or developing, market-oriented or centrally planned. Interpretations will vary, but must share certain general features and must flow from a consensus on the basic concept of sustainable development and on a broad strategic framework for achieving it." (WCED, 1987)*

The definition of sustainable development above, provided by the Brundtland report, is commonly used today. The World Bank provides another description, including the concept of the three pillars of sustainable development: economic growth, environmental stewardship, and social inclusion (The World Bank, 2017). The three pillars, also referred to as the three dimensions of sustainability, are often seen under two models: the Venn diagram model, and the "bull's eye" model (see Figure 3-1). The Venn diagram model implies that each of the dimensions are equally important and overlapping. The bull's eye model implies that the economy is a part of human society, which is itself a part of the environment (see e.g. Scott Cato, 2009).

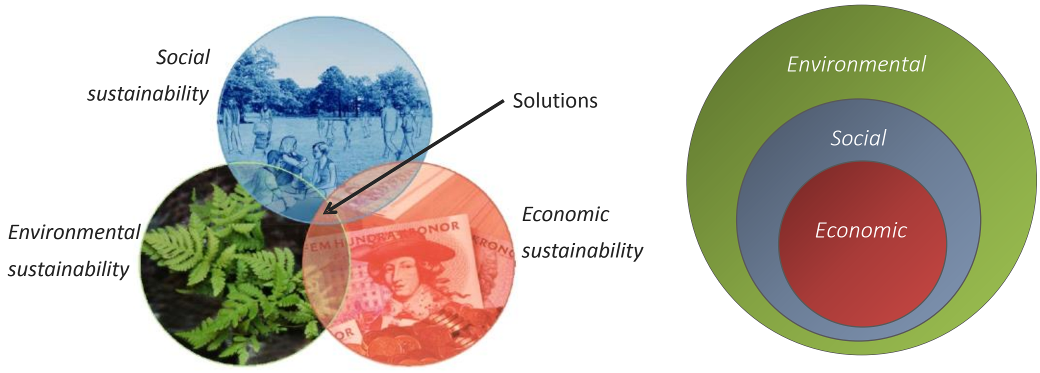

Figure 3-1. Two common sustainability models; Venn diagram (left) and Bull's eye (right). (Rosén et al., 2015)

Recent focus on sustainable development worldwide has been on the 2030 Agenda for Sustainable Development[4], which outlines 17 sustainable development goals, with 169 accompanying targets, found in more detail on the UN website[5] (United Nations, 2015). The goals came into force in 2015.

3.2 The Sustainable Remediation Concept

Remediation of contaminated land, or contaminated land management (CLM), has long been considered a sustainable action (Bardos et al., 2011), supporting the goals of sustainable development by helping to conserve land as a resource, preventing the spread of pollution to air, soil and water, and reducing the pressure for development on greenfield sites (Bardos et al., 2002). However, though the positive effects of risk reduction to human health and the environment are often focused on, remediation projects are typically associated with negative effects, such as use of fossil fuels (CO_2 emissions), production of waste, and significant noise and dust on-site (Bardos et al., 2011; Kuppusamy et al., 2016; USEPA, 2008a). This has led, in the past decade, to an increased awareness of the contradictory effects of remediation and the sustainable remediation concept (Bardos et al., 2014). Sustainable remediation can be broadly defined as:

> *"A remedy or combination of remedies whose net benefit on human health and the environment is maximized through the judicious use of limited resources." (US Sustainable Remediation Forum, 2009)*

A number of international networks and forums dealing with sustainable remediation, listed and described in Table 3-1 below, have helped to spread the concept, proposing different frameworks, methods and tools for assessing remediation projects. The Sustainable Remediation Forum - United Kingdom (SuRF-UK) propose a framework and set of sustainability indicators as a basis to support sustainability assessment of remediation projects (SuRF-UK, 2010; SuRF-UK, 2011). A recently published ISO standard provides procedures

[4] A/RES/70/1 – Transforming our world: the 2030 Agenda for Sustainable Development
[5] http://www.un.org/sustainabledevelopment/sustainable-development-goals/

for Sustainable Remediation (ISO, 2017). The United States Environmental Protection Agency (US EPA) has developed the Green Remediation concept for the national Superfund program (see e.g. US EPA, 2008b; Hadley & Harclerode, 2015).

Table 3-1. Key networks and forums involved in sustainable remediation worldwide. Adapted from Anderson (2017).

Network / Forum	Description
Sustainable Remediation Forum (SURF) (International)	Initiated in 2006 to "promote the use of sustainable practices during cleanup activities" (SURF, 2017). Published white paper (US Sustainable Remediation Forum, 2006) and framework (Holland et al., 2011). SuRF groups are now found in 12 different countries. SuRF-UK has published a Framework, Indicator Set, and Management Practices. (CL:AIRE, 2017, SuRF-UK, 2010; SuRF-UK, 2011).
Common Forum (EU)	Initiated in 1994. Mission includes being a platform for knowledge exchange as well as for discussion on policy, research, technical and managerial concepts of contaminated land in Europe. (Common Forum, 2017)
Network for Industrially Co-ordinated Sustainable Land Management in Europe (NICOLE)	"The overall objective of NICOLE is to pro-actively enable European industry to identify, assess and manage industrially contaminated land efficiently, cost-effectively, and within a framework of sustainability." (NICOLE, 2017)
Interstate Technology and Regulatory Council (ITRC) (United States)	"A public-private coalition working to reduce barriers to the use of innovative air, water, waste, and remediation environmental technologies and processes." (ITRC, 2017)

3.3 Assessment Methods

A number of assessment methods and have been presented to assess the sustainability of remediation alternatives of contaminated sites. Different frameworks have been presented attempting to organize and categorize tool types and methods. A framework proposed by Ness et al. (2007) considered the temporal characteristics, coverage areas, and integration of nature-society systems of methods, tools, and indicators. The framework consists of three umbrellas: (1) indicators and indices, (2) product-related assessment tools, and (3) integrated assessment.

Within the SuRF-UK sustainable remediation framework, it is recommended that a tiered approach is used to support decision-making, from simple qualitative approaches (checklist and conversations between stakeholders), to semi-quantitative multi-criteria analysis (MCA), to quantitative analysis such as cost-benefit analysis (CBA) (SuRF-UK, 2010). The framework outlines boundaries to define in a sustainability assessment: criteria to evaluate; system; component lifecycle; spatial boundary; timescales. SuRF-UK (2010) presents a table with selected decision support techniques that are relevant to sustainable remediation assessment, showing whether methods (techniques) are quantitative or qualitative, whether contaminated land management (CLM) application exists, as well as the scope of analysis from limited (narrow) to wide-ranging, see Table 3-2.

Table 3-2. Decision support techniques with relevance to sustainable remediation assessments (adapted from SURF-UK, 2010). Qual=Qualitative; Quan=Quantitative; CLM=Contaminated Land Management; "-" = Technique has no coverage. Newer methods may exist which are not included.

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

Three techniques which are seen in Table 3-2 to incorporate narrow to wide quantitative assessment of the three sustainability dimensions, are MCA, CBA and CEA. Multi-criteria analysis (MCA) is a general term for a method which provides transparent and structured (qualitative, quantitative or semi-quantitative) assessment of alternatives with respect to a predetermined set of indicators (e.g. SuRF-UK sustainability indicators) (Belton & Stewart, 2002; DCLG, 2009). Multi-criteria decision analysis (MCDA) is the term used when a ranking of alternatives is produced, typically including weighting and scoring of criteria and sensitivity analysis of results. Methods for calculating a ranking for alternatives can be of different types, e.g. linear additive, multi-attribute, non-compensatory. Cost-benefit analysis (CBA) is a common method which relies on welfare economics, weighing the positive and negative economic effects of alternatives to society. Costs and benefits, including externalities, are adjusted with time and expressed as a net present value (NPV) (Pearce et al., 2006; Söderqvist et al., 2015). Cost-effectiveness analysis (CEA), is similar to CBA, but focuses solely on the costs of alternatives in achieving a specified objective (DCLG, 2009).

3.4 Decision Support Tools

Decision support tools (DSTs) have been developed to help assess soil and groundwater remediation alternatives. Brief descriptions for a number of available tools is provided in Table 3-3. The tools listed range in the type of assessment used, inclusion of quantitative or qualitative measurement, scope, and purpose. It should be noted that the tools mentioned here do not include assessment of total redevelopment but only assessment of the actual remediation strategies. Several tools without information available in English have been left out of the list, such as HVS (OVAM; Van Gestel, 2015). A more exhaustive list can be found in Anderson (2017) and Brinkhoff (2011).

Table 3-3. List of decision support tools for remediation of contaminated sites. Adapted from Anderson (2017).

Name	Description
CO_2 Calculator (Praamstra, 2009)	• Developed by a consortium of Dutch remediation industry specialists • Environmental footprint (CO_2 emissions) calculator
SiteWise™ (US Navy, 2013)	• Developed by Battelle with the US Navy, U.S. Army Corps of Engineers, and Army • Excel-based tool calculating environmental footprint of remedial alternatives
Sustainable Remediation Tool (SRT) (USEPA, 2016)	• Developed in 2010 by the US Air Force • Calculates energy consumption, emissions, financial costs, and risk of injury to workers

GoldSET© (Golder Associates, 2017)	• Initially developed by Golder Associates solely for site remediation, but has evolved to use in other large-scale infrastructure engineering projects • Multi-Criteria Decision Analysis (MCDA) tool using both quantitative and qualitative input in the three sustainability dimensions: Environmental, Social, Economic • Includes a qualitative evaluation of potential technical performance
SCORE: Sustainable Choice Of REmediation (Rosén et al., 2015) CHALMERS UNIVERSITY OF TECHNOLOGY	• Developed in 2014 by Chalmers University of Technology • MCDA method and tool assessing remediation alternatives in the three dimensions of sustainability, both qualitatively and quantitatively • Includes CBA, uncertainty analysis, and sensitivity analysis • Includes consideration of soil function and project risks
Austrian National Remediation Fund model (Austrian DST) (Döberl et al., 2013)	• Excel tool based on a modified cost-effectiveness analysis • Overall objectives assessed: Environment, Local Development, Project Stability
Decision Support sYstem for Requalification of contaminated sites (DESYRE) (Carlon et al., 2007)	• GIS-based decision support system (DSS) • Structures into six interconnected modules: characterization, socio-economic, risk assessment, technological assessment, residual risk assessment, decision
Decision Support Tool Finland (Finnish DST) (Sorvari & Seppälä, 2010)	• Excel based MCDA DST • Four decision criteria: achievable risk reduction, costs, environmental effects, and other factors
"MCA tool" **(**Søndergaard et al., 2017)	• Semi-quantitative (LCA), linear additive MCA method • Five criteria: Environment, Society, Economy, Remediation Effect, Time

Several review studies of available DSTs have been published. Beames et al. (2014) study how the choice of sustainability appraisal tool, and its respective indicators and methods, affects the end choice of remediation alternative. Four tools were compared and analyzed in the study. It was seen that the tool structures, assessment scope, and weighting procedures differed between the tools, influencing the results generated. Huysegoms & Cappuyns (2017) performed a critical review of thirteen tools specifically developed to assess the sustainability of site remediation alternatives. The analysis was based on six criteria; environmental, economic, and social, based on the SuRF-UK criteria framework, as well as time, uncertainty, and user friendliness. It was found that the three best performing tools in inclusion of criteria from the SuRF-UK framework were GoldSet, SCORE, and HVS. It was found that there was an imbalance in the way sustainability was considered amongst the tools, with environmental criteria generally favoured over economic and social aspects. Inconsistency in terminology used within the field, was also highlighted. The study emphasized the need for tools to be user-friendly, flexible, and transparent. Study on inclusion of social indicators in DSTs has been performed by Cappuyns (2016), Harclerode et al. (2013), Harclerode et al. (2015). It was found that more recently published DSTs, SCORE and OVAM SB (HVS), paid significantly higher attention to social aspects (Cappuyns, 2016). The SCORE method and tool are described in the following section (4.1).

4 METHODS

In this chapter a short review of the methods used in this thesis is given. Section 4.1 describes the methods used in performing the literature review (Part 1). A summary of the SCORE method is provided in Section 4.2. Sections 4.3 and 4.4 describe the methods associated with the scenario analysis (Part 2) and the efficiency and effectiveness analysis (Part 3).

Figure 4-1 gives an overview of the methods used for each part of the thesis. The SCORE sustainability assessment method was applied on four case studies in Sweden. The results of the four case study assessments were then further analyzed in Part 2 (Paper I) and Part 3 (Paper II). A short description of the four case studies is given in Section 5.

Part 1 - Literature Review	**Part 2 - Paper I (Scenario Analysis)**	**Part 3 - Paper II (Efficiency and Effectiveness Analysis)**
• Literature review	• SCORE • Case Studies • Scenario Analysis	• SCORE • Case Studies • Efficiency Analysis (with indicators found in Part 1)

Figure 4-1. Overview of methodology within Parts 1-3.

4.1 Literature Review

The purpose of the literature review was to present how remediation efficiency and effectiveness are considered in literature and to map out possible efficiency and effectiveness indicators to be used in further study. The problem statement of the SAFIRE research project was written in Swedish, where the Swedish word "*effektivitet*" is used. *Effektivitet* translates to efficiency, however it is also the translation of effectiveness, and essentially covers both words (Svensk Akademisk Ordbok, 2017). As a result, the literature study, and the defined problem statement in English thereafter, included both the terms efficiency and effectiveness. Definitions are provided below for clarity.

> *Efficient: Achieving maximum productivity with minimum wasted effort or expense. Preventing the wasteful use of a particular resource. Working in a well-organized and competent way. (Oxford Dictionary, 2015)*
>
> *Efficiency: The state or quality of being efficient. (Oxford Dictionary, 2015)*
>
> *Effective: Successful in producing a desired or intended result. (Oxford Dictionary, 2015)*

Effectiveness: The degree to which something is successful in producing a desired result; success. (Oxford Dictionary, 2015)

After initial study of literature, it was found that the terms efficiency and effectiveness could be conceptualized on three different levels with respect to contaminated site remediation. Traditionally, in scientific literature, the terms are thought of as the removal efficiency and effectiveness of treatment technologies. Thousands of database search hits were found for these types of studies, the efficiency and effectiveness of treatment techniques and methods. However, both terms can be thought of on a project level and in terms of the progress of national programs. A conceptualization of the different levels was proposed (see Figure 4-2) for the purposes of the literature review. The level most relevant to the present research is the project level. Clarification of the levels is presented below.

Technical Level**:** Efficiency and effectiveness of a specific soil treatment for a specific contaminant(s).

Project Level**:** Efficiency and effectiveness of remediation projects in terms of time, cost, amounts, risk reduction, fulfillment of remediation goals etc.

National Level: Efficiency and effectiveness of a national remediation program.

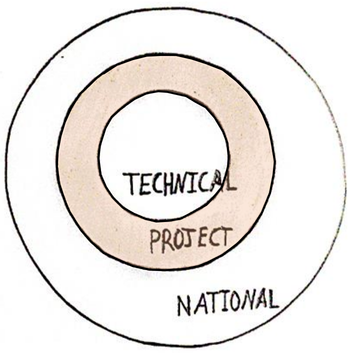

Figure 4-2. Conceptualization of the different efficiency/effectiveness levels in contaminated site remediation (from Anderson, 2017).

A database search in Scopus was performed using a number of different keyword combinations in order find relevant literature on the project and national levels, i.e. literature on project and national efficiency and effectiveness and potential indicators. A challenge was met as a result of the different nomenclature used in the industry. For example, synonymous terms are often used, including: *environmental clean-up*, *land remediation*, *contaminated land management* etc. (SURF, 2017). In addition, brownfield redevelopment, typically requiring remediation of contaminated land, was considered in order to broaden the search. Cost-effectiveness, as an established economic valuation method, was not considered as relevant, see CEA description in section 3.3.

4.2 SCORE: Sustainable Choice Of Remediation

SCORE is a Multi-Criteria Decision Analysis (MCDA) method and Excel-based tool used for assessing the sustainability of remediation alternatives at contaminated sites. SCORE has been developed at Chalmers University of Technology in collaboration with industry and government agency representatives.

Assessment of remediation alternatives in SCORE is performed within three sustainability dimensions: environmental, social, economic. SCORE assesses whether remediation alternatives lead towards sustainable development, relative to a chosen reference alternative which is typically the null alternative ("do nothing"). The method has been developed to consider sustainability of the remediation strategies and does not focus on sustainability of different end land-uses. It combines semi-quantitative environmental and social analyses with a quantitative economic analysis by means of CBA (see Söderqvist et al., 2015). Other unique features of SCORE are that it includes (1) full uncertainty analysis of decision outcomes, (2) flexibility to reflect different views on the assessment by assigning different weights to the three sustainability dimensions, though they are typically weighted equally, (3) inclusion of soil functions (see Volchko, 2013 and Volchko et al., 2013), and (4) project risks (see Brinkhoff et al., 2015).

The SCORE framework is shown below in Figure 4-3. It was developed in line with the view on the decision-making process of Aven (2012). It shows that the SCORE method supports an iterative working process, where review and updating of the assessment in conjunction with stakeholders is an important part. The SCORE conceptual model is shown in Figure 4-4. The model provides a structure to the MCDA method, and defines the boundary conditions. It shows that the *cause* of effects is the remediation taking place at a particular site, with two stressors: the Source Contamination (*SC*) and Remedial Action (*RA*). Change in source contamination typically results in positive effects due to reduced risk to humans and ecosystems. The remedial action typically results in negative effects due to e.g. use of non-renewable natural resources, emissions, and accident risks. The effects associated with the two stressors are considered at different locations, *on-site* and *off-site*. The *receptors* of both long and short-term effects are humans, ecosystems, and natural resources. The effect types are environmental, social and economic.

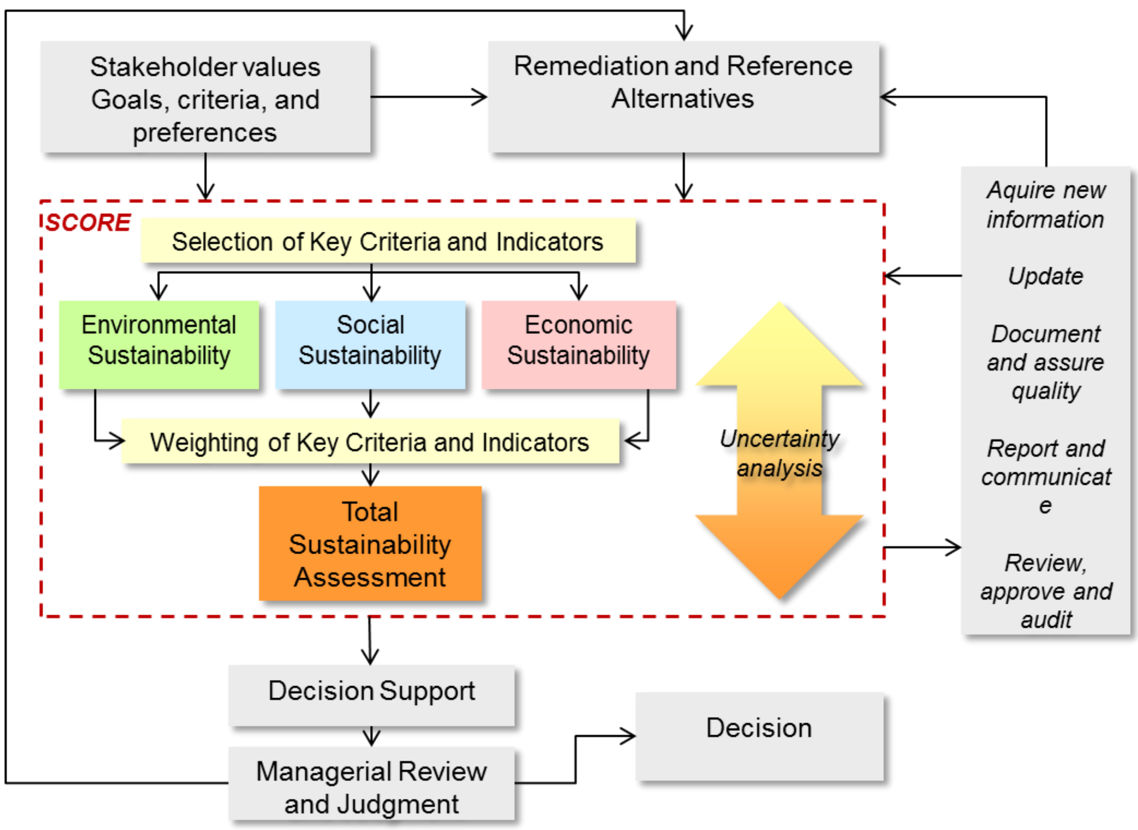

Figure 4-3. The SCORE decision support framework for remediation projects (adapted from Rosén et al., 2015).

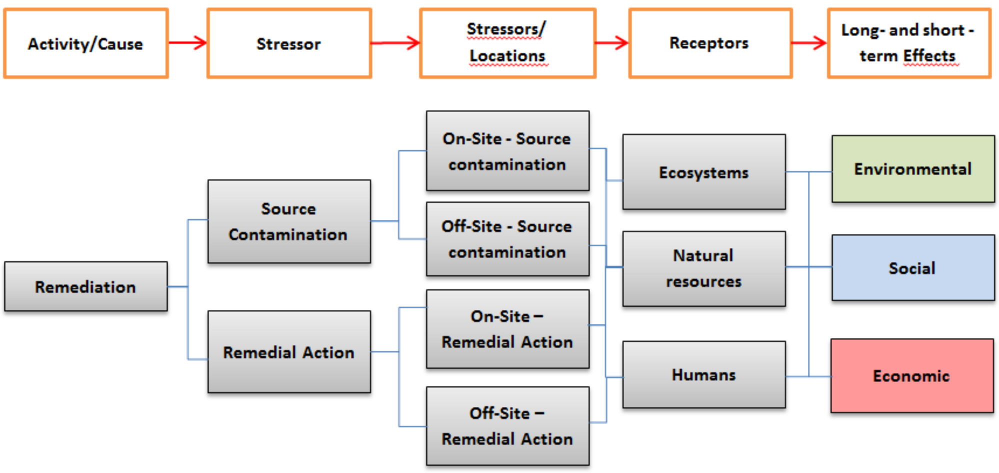

Figure 4-4. SCORE conceptual model (from Rosén et al., 2015).

Key Performance Criteria

A first step in SCORE is to select relevant criteria and indicators from the gross set of non-overlapping key performance criteria. Motivations for exclusion of criteria should clearly be given in an assessment. The key performance criteria found in SCORE were 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 key performance criteria are listed in Table 4-1. The key criteria in the environmental and social dimensions have indicators (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 only key criterion in the economic dimension is social profitability, which is assessed by means of cost-benefit analysis (CBA). The locations of the key criteria in the environmental dimension are visualized in Figure 4-5.

Table 4-1. Key performance criteria for each sustainability dimension in SCORE (from Rosén et al., 2015).

Environmental dimension	**Social dimension**	**Economic dimension**
• 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

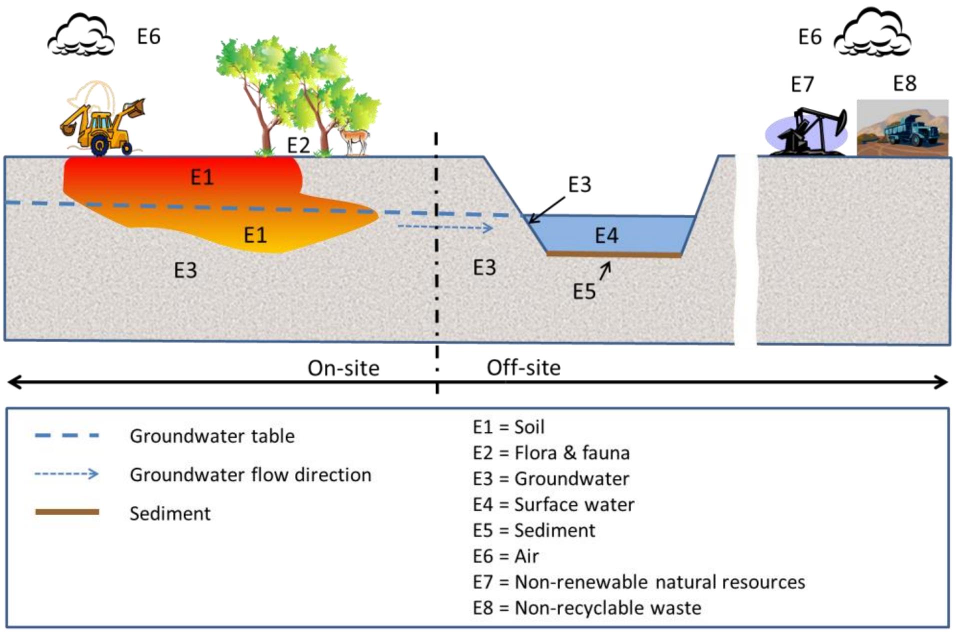

Figure 4-5. Schematic illustration of the environmental key criteria in SCORE and their spatial locations (from Rosén et al., 2015).

4.2.1 Environmental and Social Assessment

In the environmental and social dimensions, effects are assessed by means of scoring of criteria and indicators. The SCORE criteria and indicators in these two dimensions are described in detail in Table 4-2 and Table 4-3 below.

Table 4-2. Key criteria and indicators in the Environmental dimension (RA = Remedial action; SC = Source contamination) (from Rosén et al., 2015).

Key Criteria	Description	Indicators
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; 2014a).	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

Table 4-3. Key criteria and indicators in the Social dimension (RA = Remedial action; SC = Source Contamination). (from Rosén et al., 2015)

Criteria	Description	Indicators
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 (including future generations).	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

Scoring of effects (indicators) in the environmental and social dimensions is performed using the performance scale shown in Figure 4-6. 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 where examples are given to aid in an assessment. Key questions to address and suggestions for information to collect as a basis for the scoring is also provided. Scores should be assigned that best represents the expected effect, given the available information and knowledge. Motivation for each scoring should also be given for transparency.

Figure 4-6. Scoring performance scale from the SCORE tool.

4.2.2 Economic Assessment

The cost and benefit items included in the SCORE CBA are shown in Table 4-4. The social profitability is calculated in monetary terms as a net present value (*NPV*) over the time horizon of the remediation project. The main beneficiary or payer for each cost and benefit item is assigned in order to perform a distributional analysis of costs and benefits among involved stakeholders. Cost and benefit items 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 - (X)* or *very important - X*, allowing for a qualitative assessment of these items and the outcomes of the CBA. See Söderqvist et al. (2015) for a detailed description of the economic assessment methodology.

Table 4-4. Benefits (B) and costs (C) in the Economic dimension (from Söderqvist et al., 2015).

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 (see Brinkhoff et al., 2015)
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	

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

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

where $B_t = B1_t+B2_t+B3_t+B4_t$ and $C_t = C1_t+C2_t+C3_t+C4_t$ (see Table 4-4), 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.

4.2.3 Weighting of Key Criteria and Indicators

Key criteria and indicators in the environmental and social dimensions are weighted by their relative importance. The importance I of each key criterion k (k=1…K) within dimension D is given a numerical value based on the following scale: somewhat important = 1; important = 2; very important = 3. The weight of the key criterion is then calculated as:

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

The weight of each indicator j (j=1…J) within key criterion k (k=1…K) is calculated in the same way as for the key criteria in equation 2. The weights of indicators and key criteria thus have a value from 0 to 1. The total weight of all indicators and key criteria, respectively, sum to 1.

A linear additive approach is used to calculate the sustainability index H for each dimension D, as the weighted sum of the scorings for each remediation alternative i (i=1...N):

$$H_{D,i} = \sum_{k=1}^{K} w_{k,D} \sum_{j=1}^{J} w_{j,k,D} Z_{j,k,D} \qquad \text{(Eq. 3)}$$

where w_j is the weight of indicator j and Z is the score of the indicator j.

4.2.4 Sustainability Index

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

$$H_i = 100\left[W_E \frac{H_{E,i}}{Max[Max(H_{E,1..N});|Min(H_{E,1..N})|]} + W_{SC} \frac{H_{S,i}}{Max[Max(H_{S,1..N});|Min(H_{S,1..N})|]} + W_{NPV} \frac{NPV_i}{Max[Max(NPV_{1..N});|Min(NPV_{1..N})|]}\right] \qquad \text{(Eq. 4)}$$

where H_E is the score in environmental dimension, H_S is the score in the social dimension, NPV is the net present value, and W is the weight of each dimension. The weights of the dimensions are assigned according to the same scale as for the criteria. The normalized score has a value between -100 and +100. A positive score indicates that the alternative leads towards sustainable development, i.e. more positive effects than negative, relative the reference alternative. The normalized score can be used to rank the alternatives does not show a measure of sustainability in absolute terms. Figure 4-7 shows an example of results of total dimension scores and normalized total scores in the SCORE tool.

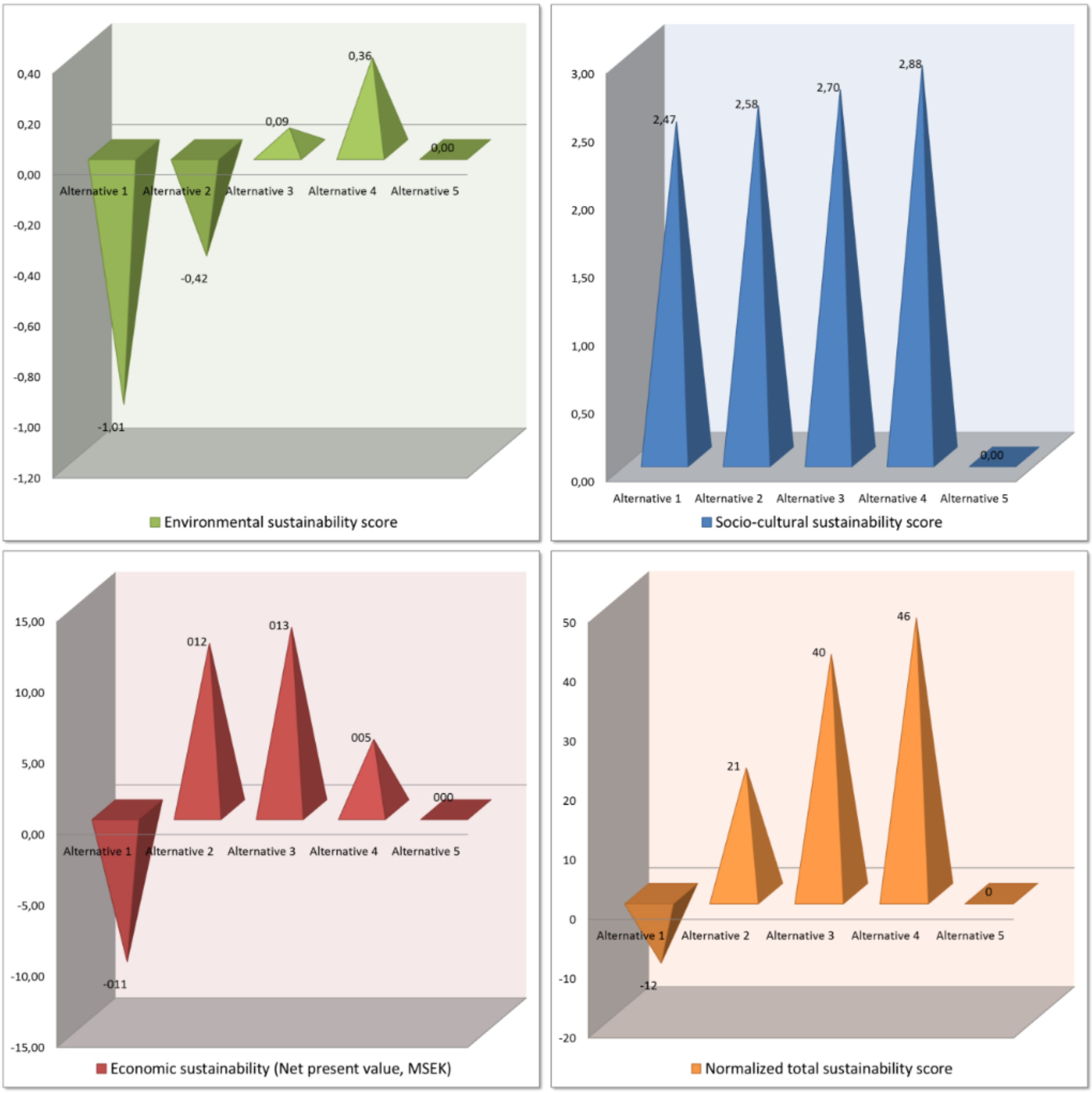

Figure 4-7. Results of a SCORE assessment of four remediation alternatives - Environmental sustainability scores (top left), Social sustainability scores (top right), Economic sustainability scores (bottom left), Total (normalized) sustainability scores (bottom right). (Rosén et al., 2015)

4.2.5 Uncertainty Analysis

Assessment of uncertainty in SCORE is achieved through a Monte Carlo simulation approach. Statistical distributions represent the uncertainties in scores (beta distributions) and cost-benefit items (log-normal distributions). Assigning uncertainty in the environmental and social dimensions is performed in three steps: (1) selection of the possible range of scorings for the specific indicator; (2) estimation of the most likely score using the performance scale presented above in Figure 4-6, and (3) assigning the uncertainty level of the scoring estimation; high, medium or low. Uncertainty levels for scores are represented by the standard deviation values shown in Table 4-5. An example of beta distributions reflecting high, medium, and low uncertainties for the same score (+2) is shown in Figure 4-8 below.

Table 4-5. Uncertainty representations of scorings (Environmental, Social) (adapted from Rosén et al., 2015).

Uncertainty level	Range	Range (Scores)	Standard Deviation
Low	All scores possible	-10 to +10	0.91
	No positive / No negative scores	-10 to 0; 0 to +10	0.46
Medium	All scores possible	-10 to +10	1.37
	No positive / No negative scores	-10 to 0; 0 to +10	0.68
High	All scores possible	-10 to +10	1.82
	No positive / No negative scores	-10 to 0; 0 to +10	0.91

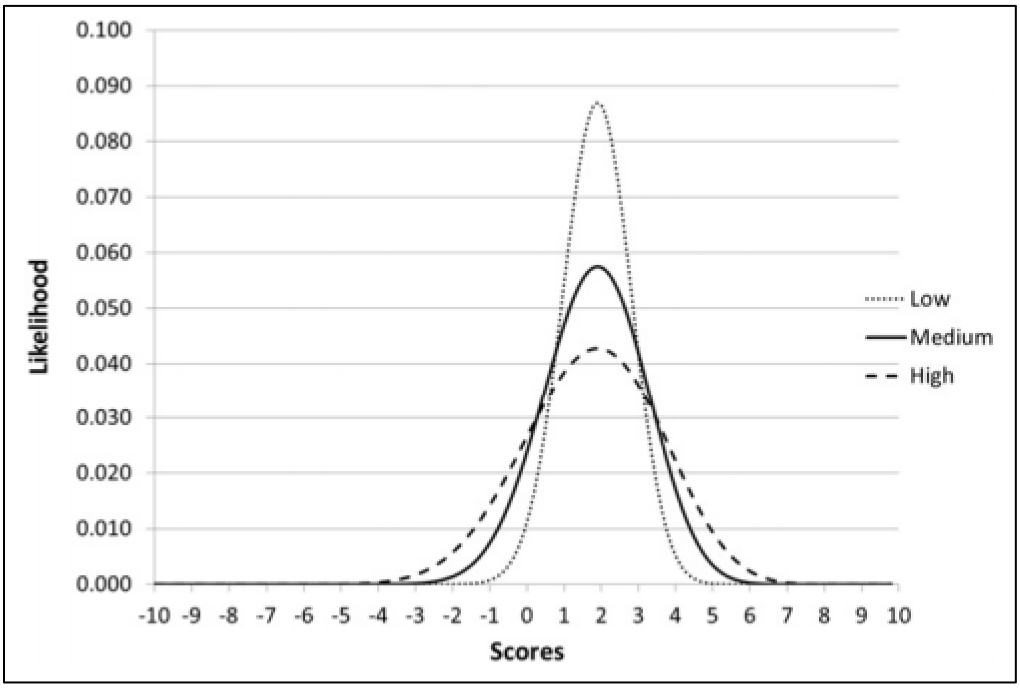

Figure 4-8. Uncertainty distributions (beta) for a most likely score of +2 with all scores possible (-10 to +10). Low uncertainty (std. dev. = 0.91), medium uncertainty (std. dev. = 1.37) and high uncertainty (standard deviation = 1.82) (from Rosén et al., 2015).

In the economic dimension, the most likely value (*MLV*) of the present value (*PV*) of each monetized cost and benefit item is assigned an uncertainty level (high, medium, low). This results in a log-normal distribution representing the uncertainty of the particular cost or benefit item. The credibility of the interval between the Lower Credibility Limit (*LCL*) and Upper Credibility Limit (*UCL*) is chosen to be 90%. Table 4-6 visualizes the relative size of this interval for the high, medium and low levels of uncertainty. The 90% credibility interval is also seen in Figure 4-9 for the three levels of uncertainties, given a mode value of *PV* equal to 1 MSEK.

Table 4-6. 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 0.60NPV to 2.39 NPV for medium uncertainty (from Rosén et al., 2015).

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

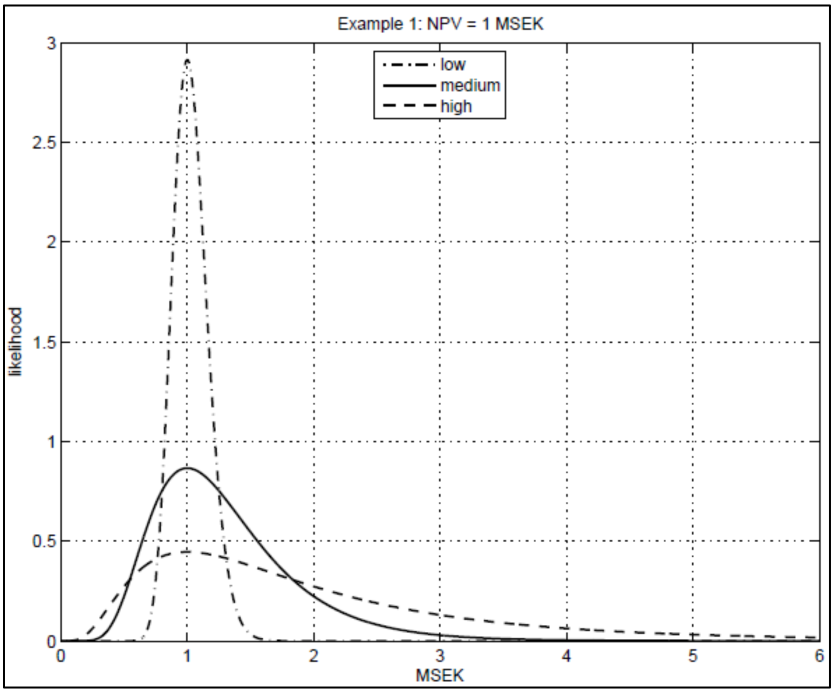

Figure 4-9. Log-normal uncertainty distributions for the three levels of uncertainty for a PV of 1MSEK (from Rosén et al., 2015).

The uncertainty of the normalized total sustainability scores is visualized in the SCORE results by providing the total mean score along with the 5th and 95th percentile values, see Figure 4-10. In addition, SCORE shows which remediation alternative has the highest probability of being most sustainable, by calculating which alternative ranked highest in the most simulation iterations, see Figure 4-11.

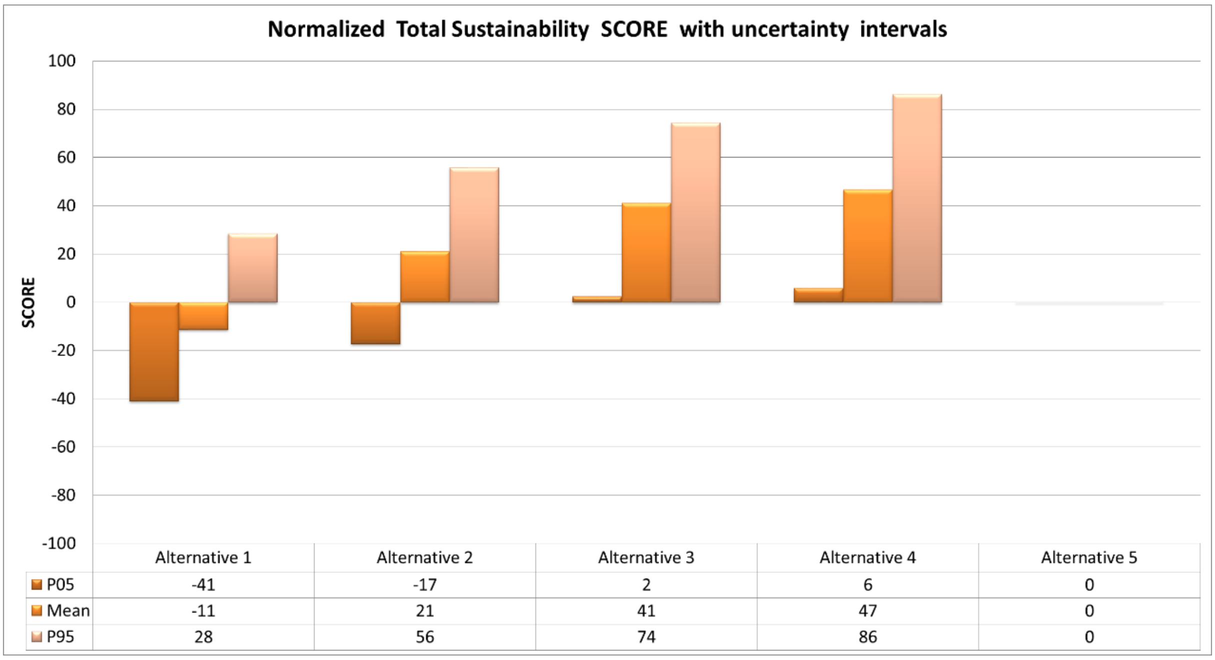

Figure 4-10. Normalized sustainability scores with uncertainty intervals (from Rosén et al., 2015).

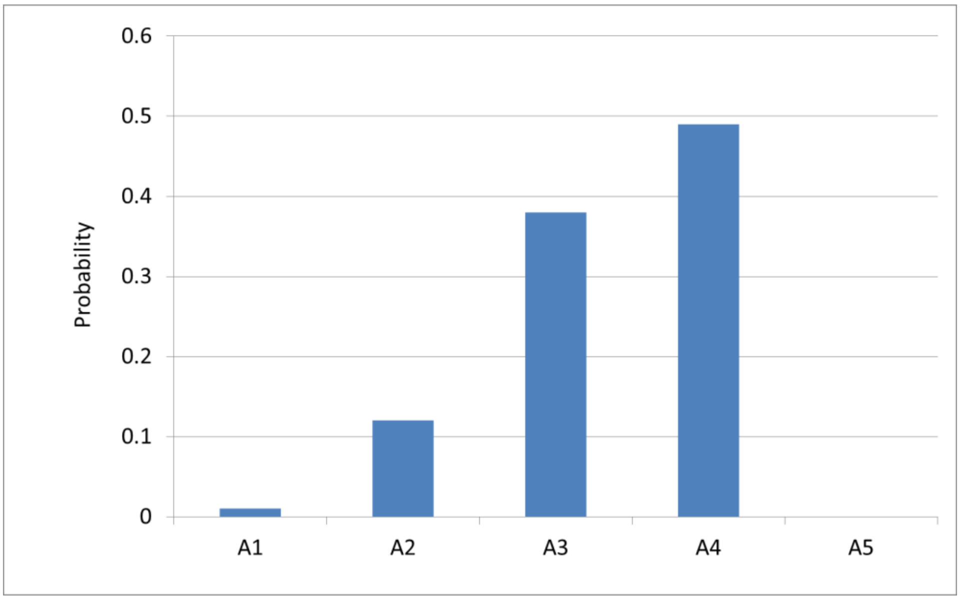

Figure 4-11. Most sustainable alternative predicted in the SCORE tool from Monte Carlo simulation (from Rosén et al., 2015).

4.3 Scenario Analysis (Paper I)

In paper I, the contribution of a full sustainability view was analyzed, compared with other possible decision support approaches. This was done by developing four alternative assessment scenarios, based on different views of what stakeholders consider to be important in an assessment. The scenarios were simulated in the SCORE tool by altering which key criteria were included in the assessment (i.e. changing the scope of the assessment), as well as the weighting of the three sustainability dimensions (i.e. changing the perspective).

A full SCORE sustainability assessment was considered as the base scenario in the study, with initial consideration of all key criteria and with equal dimension weighting. The four constructed scenarios were formulated based on a combination of four key words: *Private* vs *Public*, and *Traditional* vs. *Green*. These were described in Anderson et al. (2018a) as:

- *Private* perspective refers to focus on the economic dimension, in minimizing remediation costs and maximizing private benefits. The private scenarios give an increased weighting to the economic dimension compared with a full SCORE assessment (50%), unchanged to the social (33%), and lower weighting to the environmental dimension (17%). The Private perspective scenarios try to replicate the focus of a private problem owner, not taking externalities into account.
- *Public* perspective is considered to be an increased focus on the social and environmental dimensions (40% each), without consideration of economic benefits. A lowered economic dimension weighting (20%) is considered here. These scenarios aim to replicate the views often taken in publicly funded projects, though it could be argued that at least positive externalities should be accounted for.
- *Traditional* scope is considered as a very limited assessment, with sole focus on the positive outcomes on the environment and health due to the removal of source contamination. These scenarios attempt to replicate the most limited assessment scopes commonly seen in the past in Sweden.
- *Green* scope refers to consideration of the global secondary environmental effects of remediation; carbon emissions, use of non-renewable natural resources, and waste production (*E6, E7, E8*). These scenarios try to replicate what would be assessed in an environmental footprint type of assessment.

A summary of the four scenarios, and the specific key criteria included in each, is shown in Table 4-7 below. The dimension weighting reflecting the public and private perspectives is shown in Figure 4-12. The scenario analysis was applied on the four case studies described in Section 4.2. The scenarios did not change the weightings applied on the key criteria and indicators as part of the original assessments in the cases. The detailed dimension and key criteria weightings for each scenario and for all four cases are found in Anderson et al. (2018a).

Table 4-7. Criteria and weighting considered for each assessment scenario. (from Anderson et al., 2018a)

Scenario	Environmental	Social	Economic	Dimension Weighting
Full SCORE sustainability assessment	All Key criteria and indicators considered: *E1: Soil* *E2: Physical Impact on Flora and Fauna* *E3: Groundwater* *E4: Surface Water* *E5: Sediment* *E6: Air* *E7: Non-renewable Natural Resources* *E8: Non-recyclable Waste Generation*	All Key criteria and indicators considered: *S1: Local Environmental Quality and Amenity* *S2: Cultural Heritage* *S3: Health and Safety* *S4: Equity* *S5: Local Participation* *S6: Local Acceptance*	All Key criteria and indicators considered: *B1: Increased Property Values on Site* *B2: Improved Health* *B3: Increased Provision of Ecosystem Services* *B4: Other Positive Externalities than B2 and B3* *C1: Remediation Costs* *C2: Impaired Health due to the Remedial Action* *C3: Decreased Provision of Ecosystem Services* *C4: Other Negative Externalities than C2 and C3*	Equal Weighting
Private – Traditional (PrTr)	No secondary effects from remedial action (RA) considered.	No Social effects considered, except for S3: Health and Safety. No secondary effects from remedial action (RA) considered.	No externalities considered *(i.e. B2-B4, C2-C4 are excluded)*	Economic – 50% Environmental – 17% Social - 33%
Private - Green (PrGr)	No secondary effects from remedial action (*RA*), except for *E6, E7, E8*.	No Social effects considered, except for S3: Health and Safety. No secondary effects from remedial action (RA) considered.	No externalities considered *(i.e. B2-B4, C2-C4 are excluded)*	Economic – 50% Environmental – 17% Social - 33%
Public – Traditional (PuTr)	No secondary effects from remedial action (*RA*) considered.	No Social effects considered, except for S3: Health and Safety. No secondary effects from remedial action (RA) considered.	No Benefits or externalities considered *(i.e. B1-B4, C2-C4 are excluded)*	Economic – 20% Environmental – 40% Social - 40%
Public - Green (PuGr)	No secondary effects from remedial action (*RA*), except for *E6, E7, E8*.	No Social effects considered, except for S3: Health and Safety. No secondary effects from remedial action (RA) considered.	No Benefits or externalities considered *(i.e. B1-B4, C2-C4 are excluded)*	Economic – 20% Environmental – 40% Social - 40%

Note: Scenarios do not change scores, uncertainties, or weighting of criteria found in the full SCORE sustainability assessment for each case study.

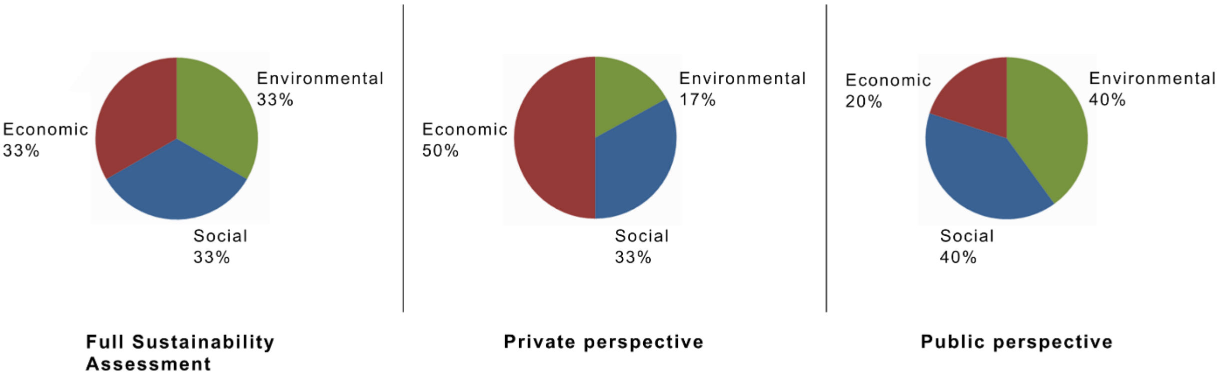

Figure 4-12. Dimension weighting reflecting the different perspectives considered in the assessment scenarios.

4.4 Efficiency and Effectiveness Analysis (Paper II)

In Paper II, the efficiency and effectiveness of remediation alternatives was studied. The same four case study sites as in Paper II were analyzed. The analysis was performed based on 20 general indicators found from literature as well as case-specific indicators for two case study sites.

Table 4-8 presents the general efficiency and effectiveness indicators selected for the analysis. Indicators were primarily found from two Swedish reports found from literature review; WSP (2014), Rosén et al. (2014). Most of the indicators from the two studies were included in the analysis, with the exception of several which were not easily quantified (e.g. cost per person in area, number of lives saved, accident risks, and number of soil species affected) and risk ratio which was deemed not to be interesting in the analysis. Risk reduction was accounted for instead by the risk reduction scores (environmental and human health) from SCORE assessment for each case study. NPV, NPV per amount soil remediated, and NPV per contaminant removal were added as indicators since they were deemed to be important, and were easily quantified from the SCORE assessments. A total of twenty indicators were selected. Classification of the indicators into efficiency and effectiveness categories was based on the definitions of the terms and descriptions of the concepts by Zidane & Olsson (2017).

Quantification of indicators came from the CBAs performed within the SCORE analyses, as well as from additional data, primarily concerning contaminant amounts and risks, obtained from the risk assessment and feasibility study reports for each case study (Landström & Östlund, 2011; Golder Associates, 2014a, 2014b; Sweco, 2011a, 2011b; Svalövs Kommun, 2016). For some case studies, certain indicators were not possible to quantify and were therefore left out.

Table 4-9 and Table 4-10 present the possible case-specific indicators identified from group interviews conducted between the SCORE evaluation team and the remediation project team for the Järpen and BT Kemi case studies. The aim of the interviews was to identify specific efficiency and effectiveness indicators related to the remediation project goals, as a complement to the indicators found from literature review. A set of open-ended questions were posed by a moderator at the beginning of the meeting, prior to any other discussions related to the SCORE methodology. Examples of questions were: *What are your thoughts on efficiency and effectiveness in remediation projects?* and *What do you think about the relation between efficiency and sustainability?*

Table 4-8. General efficiency and effectiveness indicators used to assess remediation alternatives (from Anderson et al., 2018b).

	Indicator	Description
Sustainability	Sustainability Index	Normalized mean total score as calculated in the SCORE tool. See section 3.2.
Effectiveness	NPV	Net Present Value calculated by CBA in SCORE (MSEK)
	Cancer risk reduction	Reduced cancer risks from contamination (B2b) (see description in Söderqvist et al., 2015) (Present value, MSEK)
	Anxiety reduction	Reduction in anxiety and other positive effects assumed to be reflected in increased property values in surroundings (Present Value, MSEK)
	Emissions	CO_2 emissions due to remedial action and transport of masses off-site (tonnes CO_2 equivalents)
	Consumption of clean soil	Consumption of clean soil for refilling (tonnes)
	Area remediated	Total site area remediated (m^2)
	Total contaminant removal	Total amount of primary contamination removed (tonnes)
	Total amount remediated	Total amount of soil remediated (tonnes)
	Environmental risk reduction	Weighted mean risk reduction score due to change in source contamination based on E1: Soil, E3: Groundwater, E4: Surface Water, and E5: Sediment criteria in SCORE
	Human health risk reduction	Weighted mean risk reduction score due to change in source contamination based on S3: Health and safety criterion in SCORE
Efficiency	Remediation time	Duration of remedial action (years)
	Total remediation cost	Sum of remediation cost items C1a - C1f (MSEK)
	Cost per area	Total remediation cost per total site area remediated (SEK/m^2)
	NPV per contaminant removal	Net Present Value per amount of primary contaminant removed (SEK/tonne)
	Cost per contaminant removal	Total remediation cost per amount of primary contaminant removed (SEK/tonne)
	Time per amount remediated	Remediation time per amount of soil remediated (days/tonne)
	NPV per amount remediated	Net Present Value per amount of soil remediated (SEK/tonne)
	Cost per amount remediated	Total remediation cost per amount of soil remediated (SEK/tonne)
	Cost per environmental risk reduction	Total remediation cost per weighted mean environmental risk reduction score from SCORE (MSEK/score)
	Cost per human health risk reduction	Total remediation cost per weighted mean human health risk reduction score from SCORE (MSEK/score)

Table 4-9. Possible case-specific indicators for the Järpen case study. Suggested indicators in italics are indicators that are suggested by the authors and not during the group discussion (from Anderson et al., 2018b).

Project goal	**Suggested indicators**	**Comment**	**Suggested proxy-measure in SCORE**
Goal 1: Safe and modern industrial area	No. of new work opportunities No of new industrial plots	Goal 1 is expected to be fulfilled equally well with all alternatives: the no. of work opportunities or industrial plots are not expected to differ between alternatives, neither the health risk reduction.	Local participation SC on-site – reflects new work opportunities but not number of new industrial plots.
	Health risk reduction		Health and safety SC on-site – reflects the health risk at the industrial area.
Goal 2: Increased access to water	Kilometers of walking trail	The number of km of walking trail will be the same for all alternatives. However, looking at the health risks these are expected to be higher for Alt J1 and J2 since it would make the southern shore accessible to more people without removing contamination there.	Health and Safety SC off-site –reflects the health risks rather than km of trail.
	Numbers of (new) users of walking trail and shoreline for e.g. fishing	It could be expected that the walking trail is the main driver for the number of users, but depending on how "much more" is restored in the area, the experience of the area would be different.	Local Environmental Quality and Amenity SC on- and off-site – reflects the quality of the local environment rather than the number of users.
Goal 3 and 4: Long-term recovering of the Järpenströmmen River	*Decrease in % of annual leakage to Järpenströmmen or decrease of annual load of metals (kg/yr) to Järpenströmmen*	The decrease in annual leakage and the removal of sediments will differ between alternatives as they consider different areas.	Surface water SC off-site – reflects the risk reduction rather than decrease in kg or %.
	Removal of X kg contaminated sediments		Sediment SC on- and off-site – reflects the risk reduction rather than amounts.

Table 4-10. Possible case-specific indicators for the BT Kemi case study. Suggested indicators in italics are indicators that are suggested by the authors. In the BT Kemi case, the discussions did not result in suggestions on specific indicators (from Anderson et al., 2018b).

Project goal	**Suggested indicators**	**Comment**	**Suggested proxy-measure in SCORE**
Goal 1: No risk for surrounding and fit for purpose	*Acceptable risk levels on-site*	There are no current human health risks off-site and current risk levels on-site are low. All alternatives will reach acceptable levels.	Health and safety SC on-site
	Acceptable risk levels off-site	The greatest concern regarding environmental risks is the leaching to the water course running through the area. Here, the leakage are decreased for all alternatives, but to the greatest extent when collecting leachate water and transport it further off-site.	Surface water SC, on-site
Goal 2: Creation of park and nature area	*Will there be a park and nature area (yes/no)*	Alternatives which allow the full area to be accessible will fulfil this goal. The experience of the site could potentially be different if contaminants are removed or contained.	Local Environmental Quality and Amenity SC on-site
Goal 3: Pumping of leachate water stops	*The pumping stops (yes/no)*	Only alternatives that includes no more pumping of leachate water will fulfil this criterion.	Surface water RA off-site
Goal 4 and 5: Role model and reduced stigma	*The image of Teckomatorp is changed (yes/no)*	Only alternatives that actually remove contaminants are expected to be able to reduce stigma effectively.	Local acceptance
Other goals relating to the group discussions	Minimizing time for people in the local community being worried during the remedial activities	This relates to health and safety concerns among the public during the remedial action – the more transports and excavations – the greater the concern.	Health and safety RA off-site
	Minimizing time for people in the local community being disturbed during the remedial activities	This relates to disturbances (small, transports) during the remedial action – the more transports and excavations – the greater the concern.	Local Environmental Quality and Amenity RA, off-site
	Minimizing negative environmental disturbances during the remedial activities	This relates to secondary effects of the remediation, where transports were pointed out as one aspect. The more transportation and non-renewable energy consumption, the worse.	e.g. Air RA, off-site e.g. Waste RA, off-site
	Efficient land-use	This relates to that the land use after remediation is useful, that it becomes part of the future development of the Town of Teckomatorp. Since one of the project goals is creation of park and nature area, the same indicator could be used here.	Local Environmental Quality and Amenity SC on-site

5 CASE STUDIES

This section provides description of the four case studies analyzed further in Parts 2 and 3.

The general location of the four case study sites in Sweden is shown in Figure 5-1. Details on the case studies are found in individual case study reports, see Volchko et al. (2014), Volchko et al. (2016), Rosén et al. (2016), and Brinkhoff et al. (2018). Three of the case studies included were part of the SAFIRE research project. In addition, the Hexion case study is described, which is a site first studied in the previous SCORE project.

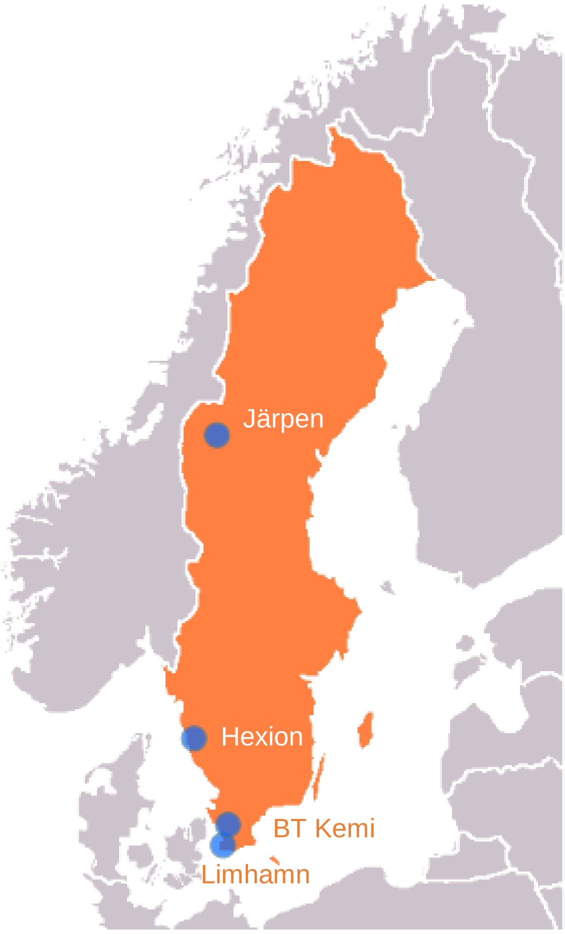

Figure 5-1. Location of the four case study sites in Sweden (map of Sweden from Wikimedia commons, Provolvere, CC-BY-SA-3.0 (from Anderson et al., 2018a).

5.1.1 Hexion

The Hexion site is an urban site located in Mölndal, a suburb of Gothenburg, Sweden. It is a former chemical production site having operated from the 1940's to 2007, producing paint and other types of binding agents (Landström & Östlund, 2011; Volchko et al., 2014). The site is approximately 35 000m^2 (see Figure 5-2) with an elevation difference from north to south of 32m, laying close to residential areas and the Mölndalsån stream. The site today is called Kvarnbyterrassen, which has been redeveloped to apartment buildings and a park area after extensive remediation. The former contaminants in the area included phthalates, lead and solvents. The project was a private exploitation project conducted by NCC Construction.

The four remediation alternatives analyzed for the Hexion case (see Table 5-1) were all based on excavation and disposal. Alternative 1 involves the most extensive excavation and transport to landfill since it is based on stricter generic guideline values stated by the Swedish EPA. Alternatives 2 to 4 are based on less strict site specific guidelines, where alternatives 3 and 4 incorporate re-use of excavated soil masses after on-site treatment. Alternative 3 considers only sieving of the soil whereas Alternative 4 incorporates both sieving and soil washing on-site and thus requires the least transport of masses and accordingly the lowest regional and global secondary effects to the environment.

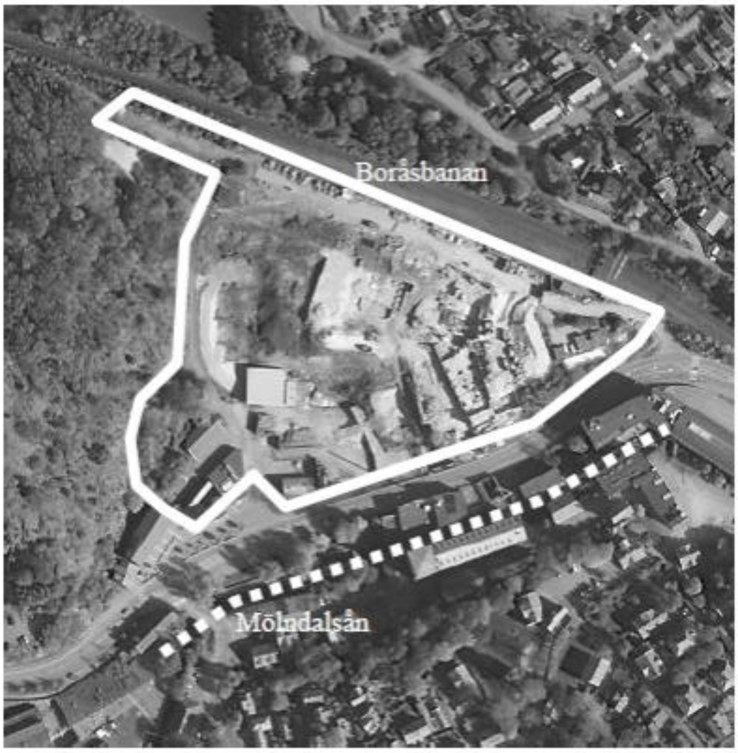

Figure 5-2. Aerial image of the Hexion site (Landström & Östlund, 2011; ©Lantmäteriet Gävle 2011/007)

Table 5-1. Remediation alternatives at the Hexion site.

Site	Reference Alternative	Alternative 1	Alternative 2	Alternative 3	Alternative 4	Alternative 5
Hexion	The site is left without remediation and with a closed chemical plant.	**H1:** Excavation and disposal of all soil with a contamination level exceeding the generic guideline values stated by SEPA. The soil is excavated and transported to a landfill.	**H2:** As Alt. 1, but based on the site-specific guideline values defined by the consultant.	**H3:** As Alt. 2, but the contaminated masses are sieved before transport to landfill or refilling at the site.	**H4:** As Alt. 3, but with the additional treatment of a soil washing process done on-site.	N/A

5.1.2 Järpen

The Järpen site has been an active industrial site since the 1880's. Previous industry has included: paper mill, scrap yard and sulphite factory (Rosén et al., 2016). The site lies on the Järpen Stream to the south and west (Figure 5-3), with a road and residential areas on the eastern side of the site. The area is contaminated with pyrite ash from the sulphite industry, with high heavy metal concentrations. The future land use is the same as the current, i.e. an industrial area, but with the addition of a public pathway along the river. The project is publicly funded with SGU as the responsible party.

Figure 5-3. Division of the Järpen site by sub-area. (from Golder, 2014a).

For the Järpen site, the five alternatives analyzed are all excavation and disposal remediation, differing based on the extent of excavation on the site and how many of the sub-areas are handled (see Table 5-2). The site is split into six different sub-areas, as seen in Figure 5-3. All of the alternatives reduce the ecological and health risks to acceptable levels in the areas that are included in the remediation. The reference alternative is that the industrial site is left as is without remediation. Alternatives 1 and 2 include excavation and disposal of areas 1 -4. However, for Alternative 1, only limited excavation of area 3 and 4 is included, requiring future land restrictions in those areas. Alternative 2 excavates these two areas to a greater depth, requiring more excavation and transport, but requiring less future land restrictions. The other three alternatives build on Alternative 1 and each other, including the south-west shoreline, area 5A, and area 5B.

Table 5-2. Remediation alternatives at the Järpen site.

Site	Reference Alternative	Alternative 1	Alternative 2	Alternative 3	Alternative 4	Alternative 5
Järpen	No remediation of the area. Current land-use and activity.	**J1:** Excavation and disposal in the main industrial area. Limited depth of excavation, requiring land-use restrictions.	**J2:** Remediation as in Alt. 1 but to a greater depth, requiring less land-use restrictions.	**J3:** Remediation as in Alt. 1, but also including the south-west shoreline area.	**J4:** Remediation as in Alt. 3, but also including the sediments outside the industrial area.	**J5:** Remediation as in Alt. 4, but also including sediments upstream.

5.1.3 Limhamn

Limhamns läge is a former cement industry area outside of Malmö. Remediation of the site has been performed in two phases, with phase 1 remediation already completed (Brinkhoff et al., 2018). The site (Phase 2) lies adjacent to a harbor and the Öresund straight, and has an area of about 68 000m^2 (see Figure 5-4). Contamination includes limestone filling material with high levels of polycyclic aromatic hydrocarbons (PAHs) and heavy metals. The project is a private exploitation project conducted by NCC construction. Future land use includes apartment buildings, recreational area, and a school to be built on site.

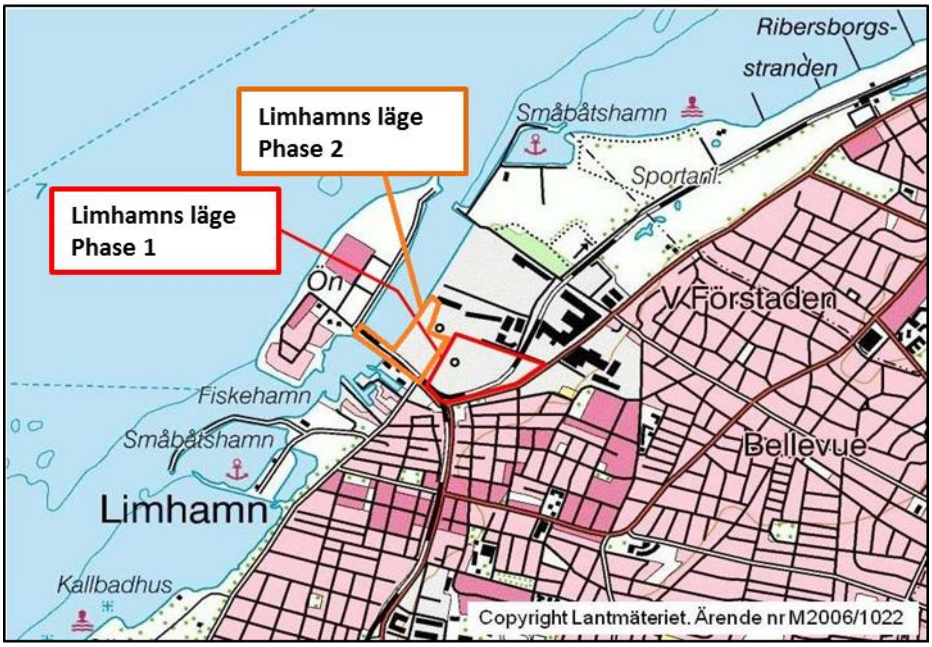

Figure 5-4. Overview map of Limhamns läge showing Phase 1 and Phase 2 areas. Phase 2 is the focus of the case study (from Brinkhoff et al., 2018; NCC, 2015).

For Limhamn, the alternatives analyzed are all excavation and disposal variations, differing based on the considered depths of the surface and deep soil layers, and on the level of protection of the soil environment (see Table 5-3). The alternatives are all fairly similar, making for quite close scoring in the assessment. Alternatives 1, 4 and 5 are the least extensive, providing little to no protection of the soil environment in the deep layer. Alternatives 2 and 3 are the most extensive, providing highest protection (50%) to the soil environment in the deeper soil layers. These two alternatives are however associated with the most extensive excavation and transport of soil masses.

Table 5-3. Remediation alternatives at the Limhamn site.

Site	Reference Alternative	Alternative 1	Alternative 2	Alternative 3	Alternative 4	Alternative 5
Limhamn	The site is left without remediation and a closed concrete plant.	**L1:** Excavation, sieving and disposal. Thickness of surface soil layer: 1.0 m. Level of protection of surface layer: 75%. Level of protection of deep layer: 25%.	**L2:** Excavation, sieving and disposal. Thickness of surface soil layer: 1.5 m. Level of protection of surface layer: 75%. Level of protection of deep layer: 50%.	**L3:** Excavation, sieving and disposal. Thickness of surface soil layer: 1.0 m. Level of protection of surface layer: 75%. Level of protection of deep layer: 50%.	**L4:** Excavation, sieving and disposal. Thickness of surface soil layer: 1.0 m. Level of protection of surface layer: 75%. Level of protection of deep layer: 0%.	**L5:** Excavation, sieving and disposal. Thickness of surface soil layer: 1.5 m. Level of protection of surface layer: 75%. Level of protection of deep layer: 0%.

5.1.4 BT Kemi

The BT Kemi site is a well-known contaminated site in southern Sweden (Skåne), due to an environmental scandal in the 1970's. Industry previously on site produced and stored pesticides (Sweco, 2011c). Initial remediation performed in the late 1970's proved to be inadequate, with phenoxy acids, chlorine resins and chlorophenols still found in the southern part of the site (see Figure 5-5) (Svalövs Kommun, 2016). Spreading of source contamination through the groundwater aquifer to the Braån stream to the north is of specific concern. Future land-use of the area is a public park and recreational area. The project is a publicly funded project with Svalövs kommun as the responsible party (Volchko et al., 2016).

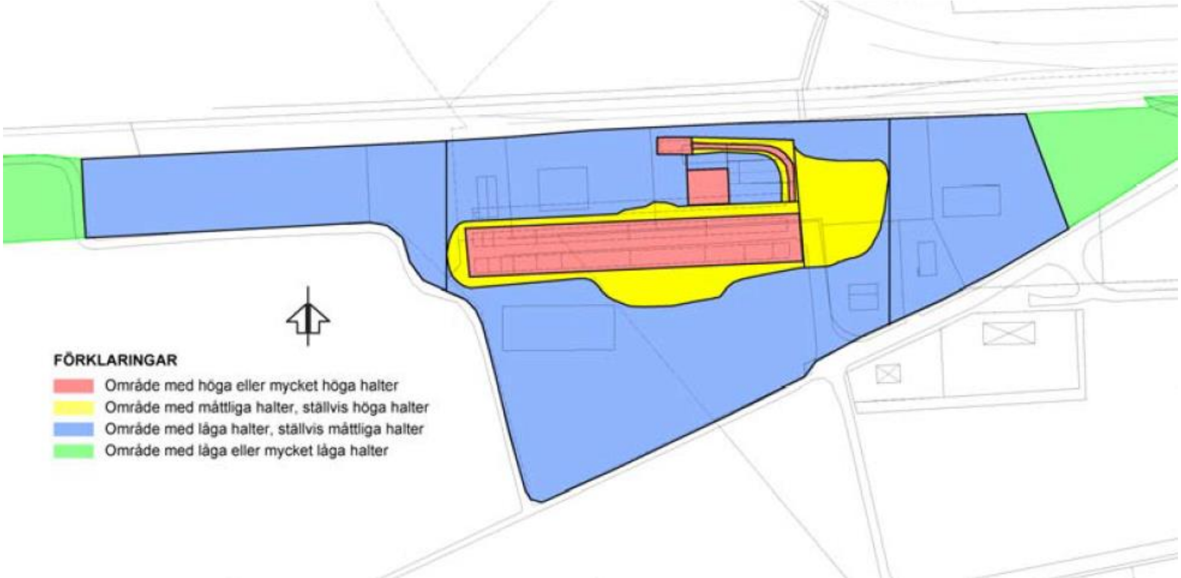

Figure 5-5. Assessed contamination levels at the BT Kemi southern site (from Sweco, 2011c). Green = low to very low levels; Blue=low to moderate levels; Yellow=moderate to high levels; Red=high to very high levels.

For BT Kemi, Alternative 1 considers pumping of contaminated groundwater to a treatment facility and covering of the area to protect humans and to be able to grow plants (see Table 5-4). However, contamination is left at the site, thus restricting future land use, as well as failing to meet the set project goals. Alternative 2 protects the spreading of contaminants in the groundwater by construction of a cover and a vertical barrier to contain the contaminant. The area is covered with clean masses as for Alternative 1, and also includes restrictions to future land-use. Alternatives 3 and 4 both consider excavation of most of the contaminants but the excavated masses are either thermally treated (Alt B3) or disposed directly (Alt B4). Alternative B5 also includes thermal treatment, but the excavation of masses is more extensive than in Alt 3 and 4.

Table 5-4. Remediation alternatives at the BT Kemi site.

Site	Reference Alternative	Alternative 1	Alternative 2	Alternative 3	Alternative 4	Alternative 5
BT Kemi	No remedial action is taken, i.e. no pumping of contaminated groundwater and no future land restrictions.	**BT1:** Pumping and treatment of contaminated water in the northern area. Enclosure and cover with 1 m clean soil. Source area covered with 2 m of clean soil for plant establishment.	**BT2:** Physical containment of the source area with vertical barriers and sealed cover, preventing contaminant migration to the upper aquifer. Area covered with 1 m clean soil for plant establishment.	**BT3:** Excavation and transport of contaminated soil to a mobile thermal treatment plant. Recycling of treated soil masses as backfill. Area covered with 1 m clean soil for plant establishment.	**BT4:** Excavation, transport and disposal of contaminated soil in a landfill. Backfilling with clean soil. Area covered with 1 m clean soil for plant establishment.	**BT5:** More extensive excavation of contaminated soil compared to alt 3 &4. Backfilling with clean soil. Thermal treatment. Area covered with 1 m clean soil for plant establishment.

6 RESULTS

This chapter provides a summary of results of Parts 1 -3. Section 6.1 presents a summary of the results from the literature review, Section 6.2 presents a summary of results from Paper I and Section 6.3 presents a summary of results from Paper II. In addition, results of a combined analysis of Papers I and II is provided in Section 6.4.

6.1 Part 1 – Literature Review

A summary of the Scopus database search is presented in Table 6-1. The approximate number of relevant articles, shown in the rightmost column, pertains to the project and national levels. A summary of efficiency and effectiveness indicators found for each of the conceptualized levels, based on the literature search, is found in Table 6-2 below. On the technical level, thousands of hits were found, with different ways of measuring the efficiency and effectiveness of treatment techniques for different types of contamination. Only some examples were therefore provided. On the national level, the Swedish, Canadian, and US national remediation programs were looked at for how they measure progress of their publicly funded programs. For all three countries, the main indicators looked at are the number of sites identified, investigated, ongoing, and completed within a given fiscal year.

On the project level, relevant indicators were found which could be used for later study within paper II. Literature on this level was mainly dominated by two Swedish reports: the first from the Swedish EPA (Rosén et al., 2014) and the second from the Confederation of Swedish Enterprise (Svenskt Näringlsiv) (WSP, 2014). The first study focuses on a broad set of indicators including many health and environmental aspects. The second study focuses on indicators pertaining more to costs and removal amounts. A conclusion from the literature review was that literature lacked indicators pertaining to risk reduction and project specific goals and that these are important to include on the project level (Anderson, 2017).

Table 6-1. Database search results in Scopus (Date: October 12th, 2017). The number of relevant articles pertains to project and national levels. The number of relevant articles was not counted when more than 150 hits were found (from Anderson, 2017).

Key Words				***Hits***	***No. Relevant***
Remediation	AND Effectiv*	AND Soil OR Site		33, 792	-
Clean-up	AND Effectiv*	AND Soil OR Site		5, 506	-
Remediation	AND Efficien*	AND Soil OR Site		35, 471	-
Clean-up	AND Efficien*	AND Soil OR Site		6, 253	-
Remediation	AND Effectiv*	AND "Contaminated site"		4, 518	-
Clean-up	AND Effectiv*	AND "Contaminated site"		888	-
Remediation	AND Efficien*	AND "Contaminated site"		4, 218	-
Clean-up	AND Efficien*	AND "Contaminated site"		826	-
Remediation OR Clean-up	AND "Efficiency indicator"	AND "Contaminated site"		5	3
Remediation OR Clean-up	AND "Effectiveness indicator"	AND "Contaminated site"		0	0
Remediation OR Clean-up	AND Effectiv*	AND "Contaminated site"	AND Indicator	800	-
Superfund	AND Effectiveness			1, 598	-
Superfund	AND Effectiveness	AND Indicator		332	-
Superfund	AND "Efficiency indicator"			5	2
Remediation OR Clean-up	AND "Efficiency indicator"	AND US		6	0
Remediation OR Clean-up	AND "Efficiency indicator"	AND Canada		10	1
Remediation OR Clean-up	AND "Contaminated site"	AND Progress		2, 535	-
Remediation OR Clean-up	AND "Contaminated site"	AND Progress	Superfund	366	4
"Contaminated land management"	AND Efficien* OR Effectiv*			216	-
"Contaminated land management"	AND Efficien* OR Effectiv*	AND Indicator		82	3
"Contaminated land management"	AND Progress	AND Indicator		44	2
"Contaminated land management"	AND Progress	AND Superfund		34	0
"Efficient remediation"				150	-
"Efficient remediation"	AND "Contaminated site"			15	2
"Effective remediation"	AND "Contaminated site"			44	0
"Project efficiency"				283	-
"Project efficiency"	AND "Contaminated site"			0	0
"Project effectiveness"				219	3
"Project effectiveness"	AND "Contaminated site"			0	0
"Project management	AND "Contaminated site"			29	1
"Project management	AND "Contaminated land"			20	2
"Remediation project"	AND "National program"			0	0
Brownfield	AND Efficien*			228	-
Brownfield	AND Efficien*	Project		87	3
Brownfield	AND Effectiv*			328	-
Brownfield	AND Effectiv*	Project		102	2

Table 6-2. Summary of efficiency and effectiveness indicators on each level (from Anderson, 2017).

Level	"Efficiency"	"Effectiveness"
National		No. sites assessed[a,b,c] No. sites started[a] No. construction completed[b] Liability reduction[a] No. sites completed[a,b,c] Sites/yr[a] Environmental Indicators[b] No. sites identified[c] No. sites ongoing[c] No. sites ongoing/completed for res. construction[c]
Project	Time per amount excavated (days/tonne) [d] Cost per amt. excavated (kr/tonne) [d] Cost per remediation area (kr/m^2) [d] Cost per amount contaminant removed (kr/kg)[d,e] Cost per risk-ratio (kr/risk-ratio) [d] Cost per person in area (kr/person) [d] Total project time (yrs)[d] Total project cost (kr)[d,e]	Cancer risk reduction (%)[d] Total amounts contamination removed (kg)[e] No. lives saved [e] Accident risks from RA [e] Area remediated (m^2) [e] Amount soil remediated (tonnes) [e] No. soils species affected [e] Surface water protection (kg/100yrs)[e] Groundwater protection (m^3/yr) [e] Emissions (kg) [e] Consumption of clean soil for refilling (tonnes) [e]
Technical	Degradation (%)[f] Removal (%)[g] Immobilization (%)[h] Remediation Time (hrs)[i] Cost (US$/m^3)[j] Cost (US$/t)[j] Translocation Factor[k]	

[a] FCSAP, 2015
[b] US EPA, 2017
[c] Swedish EPA, 2014
[d] Svenskt Näringsliv, 2014
[e] Rosén et al., 2014
[f] Jonsson et al., 2006
[g] Jonsson et al., 2008
[h] Mallampati et al., 2015
[i] Albergaria et al., 2006
[j] Mulligan et al., 2001
[k] Marchiol et al., 2004

In addition to the indicators found above, an additional useful result of the literature review on project efficiency and effectiveness came from a recent study performed by Zidane and Olsson (2017). They propose a model to conceptualize the definitions of project efficiency, project effectiveness as well as project efficacy, which were said to be interpreted in diverse ways among research scholars and practitioners. Efficacy is defined by the authors as being able to lead to an effective outcome, though it was excluded from further study since it is often synonymous with effectiveness and is a term more commonly used in medicine and pharmacology. The authors state that project efficiency relates to producing an output in a competent and qualified way, while project effectiveness relates to results accomplishing their purposes and an effective outcome. This study was useful in clarifying and confirming previous thoughts on how the two terms are thought of (as per the definitions) and relate to one another, as well as aiding in the categorization of indicators in Table 6-1. The mentioned model, adapted to remediation projects, is seen in Figure 6-1 below.

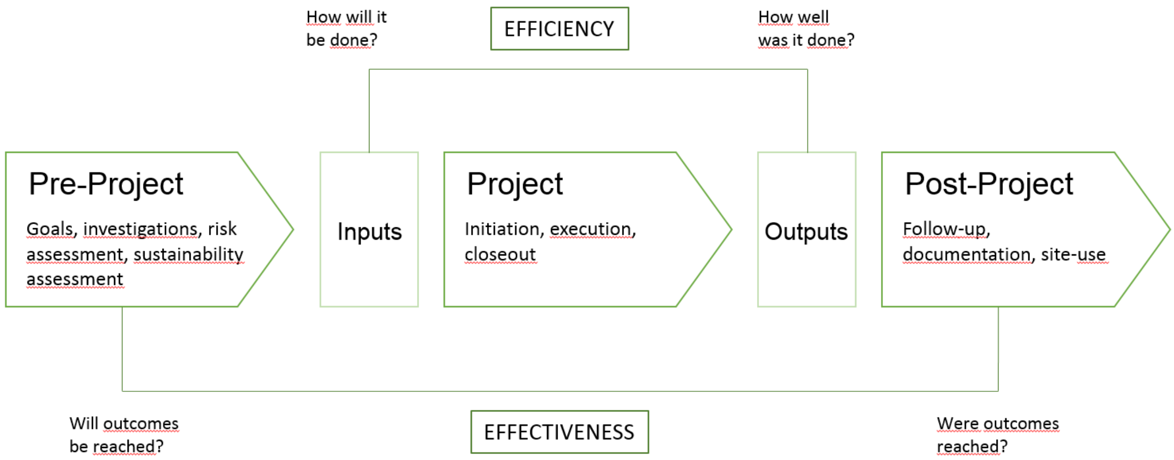

Figure 6-1. Model reflecting project efficiency, and effectiveness. Adapted from Zidane & Olsson (2017).

6.2 Part 2 – Scenario Analysis (Paper I)

The results of the scenario analysis for each of the four case studies are found below in Figure 6-2 to Figure 6-5. The figures show the probabilities of each remediation alternative obtaining the highest total normalized score across the scenarios, reflecting the level of certainty of the results. The alternative highlighted for each scenario was assessed as being the highest ranked alternative according to the considered scope and criteria weighting of each scenario. The breakdown of scores within each sustainability dimension can be found in Paper I, along with more detailed description of results. The input scores and weights for all case studies can be found as supplementary material in Paper I.

6.2.1 Hexion

For the full SCORE assessment in the Hexion case, alternative H4, with lowest secondary environmental effects (i.e. least excavation and transports) and highest social scores, had the highest probability of being the top ranked alternative. Both H3 and H4 had high probabilities of receiving the highest total score, with H3 performing best in the economic dimension but H4 performing better with respect to secondary effects in the environmental dimension. The top ranking alternative changed for all other scenarios, with H3 performing best in the Private-Traditional, Private-Green and Public-Green scenarios, with low certainty. The most extensive excavation remediation, H1, performed best in the Public-Traditional scenario, with rather high certainty.

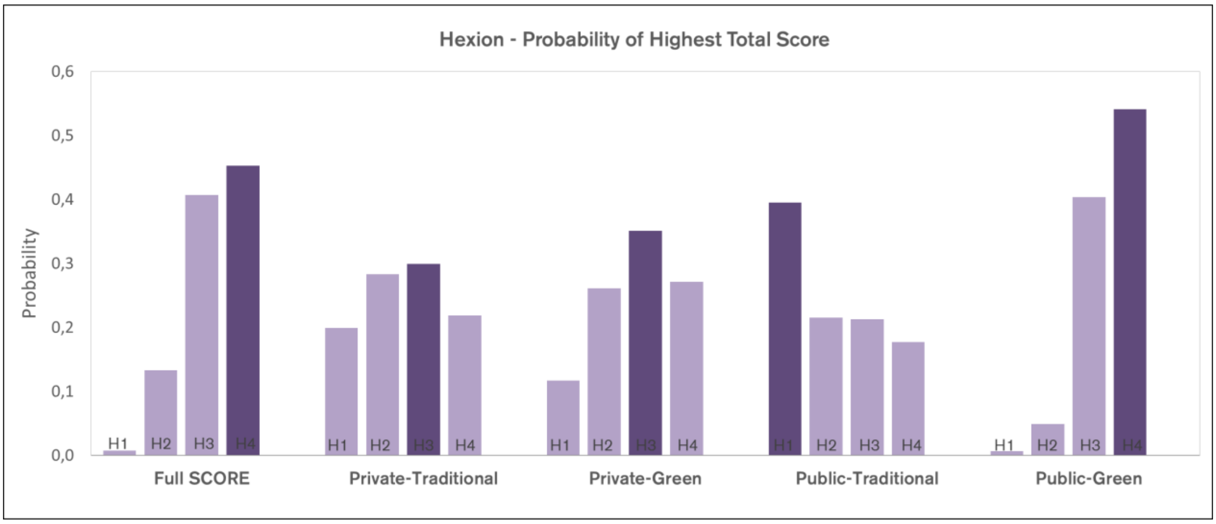

Figure 6-2. Probability of each alternative (H1-H4) obtaining the highest total normalized score for the Hexion case study. The highest probability alternative for each scenario is highlighted (from Anderson et al., 2018a)

6.2.2 Järpen

In the Järpen case, alternative J4, the second most extensive excavation alternative, was assessed to be the most sustainable based on the full SCORE assessment. Alternative J4 received the highest environmental dimensions score, and thus had the best trade-off between contaminant removal and secondary environmental effects. The highest-ranking alternative was different for all other scenarios, with J3, a low-cost alternative, performing best in the private scenarios, but with quite low certainty. The most extensive excavation remediation, J5, performed best in the public scenarios with high probability. None of the scenarios favoured alternative J1 or J2, as these two alternatives did not remediate all of the sub-areas, with expected exposure of health risks to people.

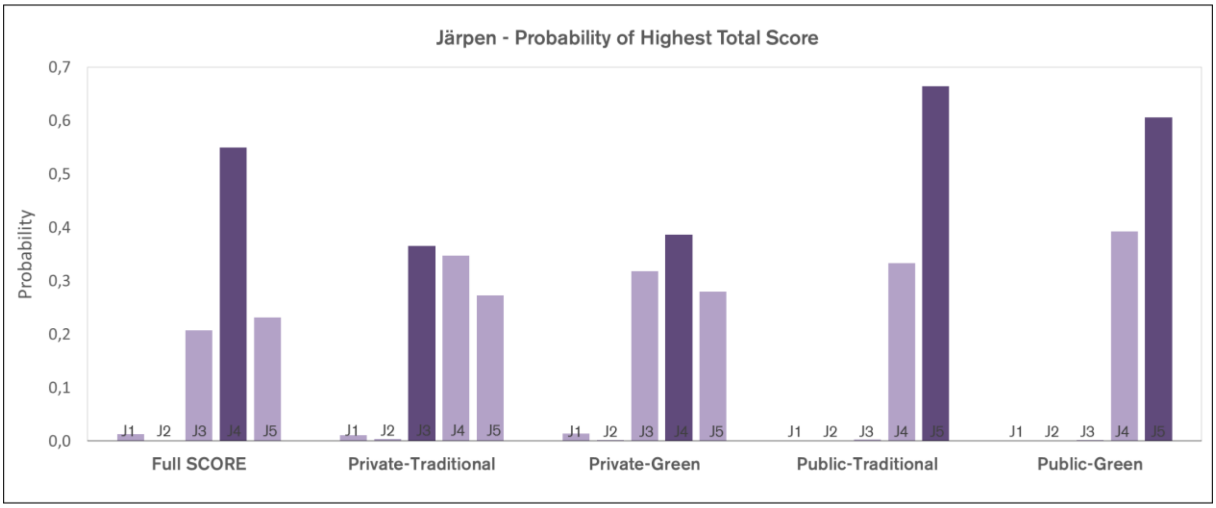

Figure 6-3. Probability of each alternative (J1-J5) obtaining the highest total normalized score for the Järpen case study. The highest probability alternative for each scenario is highlighted (from Anderson et al., 2018a).

6.2.3 Limhamn

In contrast to the Järpen case, alternative L4, the least extensive excavation alternative, was assessed to be best in the full SCORE assessment in the Limhamn case. This is as a result of the relatively high weighting to the key criteria considering secondary regional and global effects as well as the fact that the other environmental and social effects were very similar for all alternatives. The high economic domain weighting and/or high weighting of the negative secondary environmental effects allowed for alternative L4 to be assessed as best in all but one of the other scenarios, but with lower certainty than the full assessment. In the Public-Traditional scenario, L2, the next most extensive alternative, came out as being the best alternative, as a result of the low economic weighting and exclusion of secondary environmental effects.

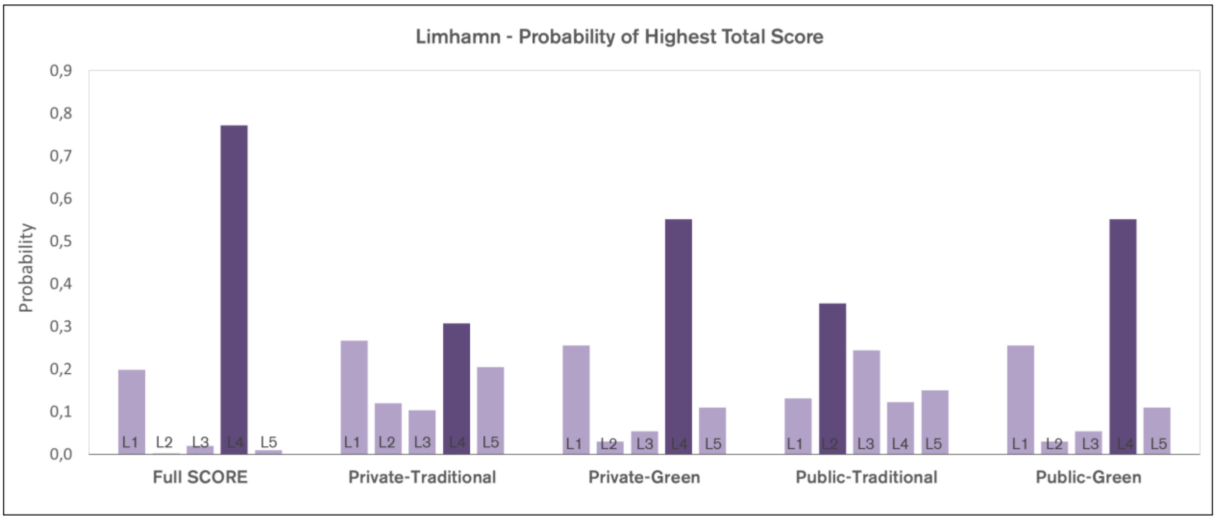

Figure 6-4. Probability of each alternative (L1-L5) obtaining the highest total normalized score for the Limhamn case study. The highest probability alternative for each scenario is highlighted (from Anderson et al., 2018a).

6.2.4 BT Kemi

The full SCORE assessment for the BT Kemi case resulted in alternative BT4, the second most extensive excavation alternative, being most sustainable. The three excavation alternatives (BT3, BT4, BT5) were favoured in the BT Kemi case, all with high probability of being the top ranking alternative. Alternative BT1 (pumping and treatment) and BT2 (physical containment) performed poorly in the social and economic dimensions, since the limited remediation in these alternatives meant that the stigma surrounding the site remained, with no positive externalities as reflected by increased property values in the surroundings. Despite the exclusion of positive externalities, alternative BT4 remained as best (with lower certainty) in the private scenarios due to compensation of high environmental and social scores, but with higher probabilities for BT1 and BT2 to have the highest total score. The most extensive alternative, BT5, performed best in the public scenarios due to the low economic weighting, given the high environmental scores from extensive contaminant removal.

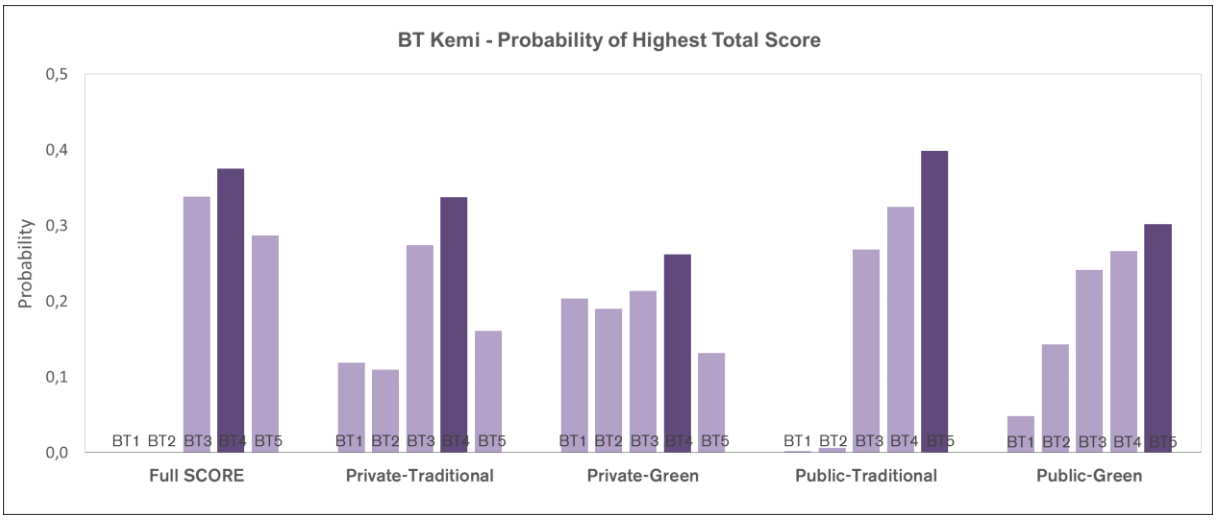

Figure 6-5. Probability of each alternative (BT1-BT5) obtaining the highest total normalized score for the BT Kemi case study. The highest probability alternative for each scenario is highlighted (from Anderson et al., 2018a).

6.3 Part 3 – Efficiency and Effectiveness Analysis (Paper II)

The results of the efficiency and effectiveness analysis for each of the four case studies are found below in Table 6-3 to Table 6-6. A detailed description of the results, along with result tables for the case-specific analysis are found in Paper II.

In the Hexion case, the most sustainable alternative H4, performed best only with respect to secondary environmental effects (emissions, consumption of clean soil for refilling). Alternative H3 performed best on the most number of indicators, as it had the highest NPV and lowest remediation costs. Despite not having the highest contaminant removal, H3 ranked highest in terms of NPV per amount remediated. H3 also had the lowest cost per environmental and human health risk reduction. Alternative H1, the most extensive alternative, based on generic guideline values, performed best on the effectiveness indicators relating to soil and contaminant removal and environmental risk reduction. In the Hexion case, all four alternatives performed equally on cancer risk reduction, anxiety reduction, area remediated, and human health risk reduction.

Alternative J4 was the most sustainable alternative in the Järpen case, which was second most extensive in terms of the number of sub-area remediated, and resulted in the best trade-off between contaminant removal and secondary environmental effects. J4 ranked highest on two efficiency indicators, cost per environmental risk reduction and human health reduction indicators, however generally performed poorly on other efficiency indicators. Alternative J5, remediating the most number of sub-areas, with highest contaminant removal, was seen to be the most effective alternative based on the selected indicators, but performed worst with respect to economic aspects to due to its high costs. Alternative J2 was seen to be efficient due to its high contaminant removal and lower costs, however by not remediating the shoreline and sediment areas, this alternative performed poorly with respect to risk reduction.

The most sustainable alternative in the Limhamn case, L4, performed best on the most number of indicators. All alternatives in the Limhamn case were very similar, involving different extents of excavation and disposal. Alternative L4 was the least extensive alternative, therefore resulting in low costs and short time with low secondary effects. The most extensive alternative, L2, was effective with respect to amounts removed and environmental risk reduction, and despite being the most expensive alternative, it was efficient with respect to cost per amounts removed.

Alternatives BT3, BT4, and BT5 performed best in the SCORE assessment since these alternatives resulted in removal of source contamination at the site, as opposed to in-situ methods BT1 and BT2, thus better contributing to the reduction of the negative stigma surrounding the site. Alternative BT4 was most sustainable, involving disposal of contaminated masses as opposed to thermal treatment and soil reuse. BT4 had the highest NPV, and ranked highest in terms of cost and NPV per contaminant removal and cost per human health risk reduction. Alternative BT5, the most extensive alternative was seen to be the most effective, not just as a result of greatest removal and risk reduction, but also from recycling of contaminated masses. Alternative BT1 and BT2, consisting of pumping and treatment and physical containment, respectively, performed poorly with respect to risk reduction and NPV. However, given that these are in-situ methods, a number of indicators pertaining to amounts removed were not able to be quantified and compared to the excavation and disposal alternatives. BT1 and BT2 performed best with respect to remediation time, costs, and secondary environmental effects.

The case specific indicators for the Järpen site generally show a progressive increase of scores from alternative J1 to J5 for the first two goals, which relate to increased access to water, and the long-term recovery of the Järpenströmmen River. The most extensive alternatives, J3-J5, therefore perform best overall. *Local Participation SC (on-site)* and *Health and Safety SC (on-site)*, both related to the first goal of a safe and modern industrial area, which perform equally across alternatives.

The case-specific indicators for the BT Kemi case show that the excavation alternatives (BT3-BT5) perform best with respect to the first five goals. These relate mainly the removal of source contamination on-site as well as to Local acceptance (removing the stigma). The additional indicators outlined, pertaining mainly to social and environmental secondary effects, better support the in-situ alternatives (BT1, BT2).

Table 6-3. Efficiency and effectiveness of remediation alternatives for the Hexion case study (from Anderson et al.,2018b). Colour scaling highlights the best (green) and worst (red) alternative. Yellow highlighting is used for the midpoint on each local scale as well as for when alternatives perform equally on a given indicator.

	Indicator	Alternative **H1** Excavation and disposal. Generic guideline values.	Alternative **H2** Excavation and disposal. Site-specific guideline values.	Alternative **H3** As H2, but with soil sieving	Alternative **H4** As H3, but with soil washing
	Sustainability Index (Norm. Score)	-12	20	41	44
Effectiveness	NPV (MSEK)	-8.00	8.41	9.63	3.77
	Cancer risk reduction (MSEK)	0.0003	0.0003	0.0003	0.0003
	Anxiety reduction (MSEK)	0.07	0.07	0.07	0.07
	Emissions (tonnes CO2-equivalents)	590	376	352	332
	Consumption of clean soil for refilling (tonnes)	29537	17420	10520	0
	Area remediated (m^2)	35000	35000	35000	35000
	Total amount primary contamination removed (tonnes)	52.5	47.4	47.4	47.4
	Amount soil remediated (tonnes)	91114	57160	57160	57160
	Environmental risk reduction (score)	3.1	2.2	2.2	2.2
	Human health risk reduction (score)	4	4	4	4
Efficiency	Remediation time (years)	3	3	3	3
	Total remediation cost (MSEK)	54.0	40.5	37.3	43.3
	Cost per remediation area (SEK/m^2)	1542	1158	1066	1238
	NPV per contaminant removal (SEK/tonne)	-152381	177426	203165	79536
	Cost per contaminant removal (SEK/tonne)	1027810	855063	787131	913924
	Time per amount remediated (days/tonne)	0.012	0.019	0.019	0.019
	NPV per amount remediated (SEK/tonne)	-88	147	168	66
	Cost per amount remediated (SEK/tonne)	592	709	653	758
	Cost per environmental risk reduction (MSEK/score)	17.3	18.2	16.8	19.5
	Cost per human health risk reduction (MSEK/score)	13.5	10.1	9.3	10.8

Table 6-4. Efficiency and effectiveness of remediation alternatives for the Järpen case study (from Anderson et al.,2018b). Colour scaling highlights the best (green) and worst (red) alternative. Yellow highlighting is used for the midpoint on each local scale as well as for when alternatives perform equally on a given indicator.

	Indicator	Alternative **J1** Excavation and disposal, limited depth	Alternative **J2** As J1, but to greater depth	Alternative **J3** As J1, but including the south-west shoreline area	Alternative **J4** As J3, but including sediments downstream	Alternative **J5** As J4, but including sediments upstream
	Sustainability Index (Norm. Score)	-10	-29	14	17	10
Effectiveness	NPV (MSEK)	-51.6	-67.5	-55.3	-69.0	-86.7
	Cancer risk reduction (MSEK)	0.46	0.46	0.46	0.46	0.46
	Anxiety reduction (MSEK)	-	-	-	-	-
	Emissions (tonnes CO2-equivalents)	918	1184	982	1043	1222
	Consumption of clean soil for refilling (tonnes)	20460	31900	23100	23100	23100
	Area remediated (m^2)	38776	38776	41801	49415	53197
	Total amount primary contamination removed (tonnes)	34000	45000	36700	39200	46700
	Amount soil remediated (tonnes)	44660	60060	47300	50600	60500
	Environmental risk reduction (score)	2.2	2.7	3.9	5.4	6.0
	Human health risk reduction (score)	3	3	6.5	8	9
Efficiency	Remediation time (years)	0.50	0.50	0.50	0.75	0.75
	Total remediation cost (MSEK)	53.7	68.8	57.2	70.4	87.8
	Cost per remediation area (SEK/m^2)	1386	1774	1368	1425	1650
	NPV per contaminant removal (SEK/tonne)	-1519	-1500	-1507	-1760	-1857
	Cost per contaminant removal (SEK/tonne)	1580	1529	1559	1796	1880
	Time per amount remediated (days/tonne)	0.0041	0.0030	0.0039	0.0054	0.0045
	NPV per amount remediated (SEK/tonne)	-1156	-1124	-1169	-1364	-1433
	Cost per amount remediated (SEK/tonne)	1203	1146	1209	1391	1451
	Cost per environmental risk reduction (MSEK/score)	24.6	25.6	14.5	12.9	14.6
	Cost per human health risk reduction (MSEK/score)	17.9	22.9	8.8	8.8	9.8

Table 6-5. Efficiency and effectiveness of remediation alternatives for the Limhamn case study (from Anderson et al.,2018b). Colour scaling highlights the best (green) and worst (red) alternative. Yellow highlighting is used for the midpoint on each local scale as well as for when alternatives perform equally on a given indicator.

	Indicator	Alternative **L1** Excavation, sieving and disposal. 1.0m surface layer. 75% / 25% protection	Alternative **L2** Excavation, sieving and disposal. 1.5m surface layer. 75% / 50% protection	Alternative **L3** Excavation, sieving and disposal. 1.0m surface layer. 75% / 50% protection	Alternative **L4** Excavation, sieving and disposal. 1.0m surface layer. 75% / 0% protection	Alternative **L5** Excavation, sieving and disposal. 1.5m surface layer. 75% / 0% protection
	Sustainability Index (Norm. Score)	-6	-32	-20	4	-21
Effectiveness	NPV (MSEK)	-7.1	-10.6	-10.0	-5.2	-7.0
	Cancer risk reduction (MSEK)	0.0037	0.0037	0.0037	0.0037	0.0037
	Anxiety reduction (MSEK)	-	-	-	-	-
	Emissions (tonnes CO2-equivalents)	29.22	49.37	39.33	23.50	34.62
	Consumption of clean soil for refilling (tonnes)	3062	14775	7360	4228	12686
	Area remediated (m^2)	68000	68000	68000	68000	68000
	Total amount primary contamination removed (tonnes)	350.1	708.4	497.6	266.6	493.0
	Amount soil remediated (tonnes)	21987	44482	31248	16744	30960
	Environmental risk reduction (score)	3.3	6.7	5.3	2.0	3.3
	Human health risk reduction (score)	1	1	1	1	1
Efficiency	Remediation time (years)	0.15	0.18	0.18	0.12	0.18
	Total remediation cost (MSEK)	7.0	10.5	9.9	5.1	6.9
	Cost per remediation area (SEK/m^2)	102	154	145	75	101
	NPV per contaminant removal (SEK/tonne)	-20152	-14954	-20089	-19329	-14141
	Cost per contaminant removal (SEK/tonne)	19895	14759	19846	19063	13942
	Time per amount remediated (days/tonne)	0.0025	0.0015	0.0021	0.0007	0.0021
	NPV per amount remediated (SEK/tonne)	-321	-238	-320	-308	-225
	Cost per amount remediated (SEK/tonne)	317	235	316	304	222
	Cost per environmental risk reduction (MSEK/score)	2.1	1.6	1.9	2.5	2.1
	Cost per human health risk reduction (MSEK/score)	7.0	10.5	9.9	5.1	6.9

Table 6-6. Efficiency and effectiveness of remediation alternatives for the BT Kemi case study (from Anderson et al.,2018b). Colour scaling highlights the best (green) and worst (red) alternative. Yellow highlighting is used for the midpoint on each local scale as well as for when alternatives perform equally on a given indicator.

	Indicator	Alternative **BT1** Pumping and treatment and enclosure	Alternative **BT2** Physical containment	Alternative **BT3** Excavation, thermal treatment, soil recycle	Alternative **BT4** Excavation, disposal, backfilling	Alternative **BT5** Extensive excavation, thermal treatment, soil recycle
	Sustainability Index (Norm. Score)	7	22	58	59	56
Effectiveness	NPV (MSEK)	-62.3	-94.3	49.4	57.6	13.0
Effectiveness	Cancer risk reduction (MSEK)	-	-	-	-	-
Effectiveness	Anxiety reduction (MSEK)	0	13.9	195.2	195.2	194.1
Effectiveness	Emissions (tonnes CO2-equivalents)	92.9	69.1	4170.7	1472.0	5710.7
Effectiveness	Consumption of clean soil for refilling (tonnes)	0	0	0	50800	0
Effectiveness	Area remediated (m^2)	0	11580	7935	7935	7935
Effectiveness	Total amount primary contamination removed (tonnes)	0	0	1.7	1.7	2.0
Effectiveness	Amount soil remediated (tonnes)	0	0	58000	58000	85500
Effectiveness	Environmental risk reduction (score)	2.9	2.6	3.6	3.6	4.3
Effectiveness	Human health risk reduction (score)	1	2	3	3	3
Efficiency	Remediation time (years)	0.33	0.75	0.83	0.83	1.00
Efficiency	Total remediation cost (MSEK)	61.9	107.6	140.0	131.5	173.2
Efficiency	Cost per remediation area (SEK/m^2)	-	9292	17643	16572	21827
Efficiency	NPV per contaminant removal (SEK/tonne)	-	-	29235782	34129147	6461538
Efficiency	Cost per contaminant removal (SEK/tonne)	-	-	82938389	77902844	85955335
Efficiency	Time per amount remediated (days/tonne)	-	-	0.0052	0.0052	0.0043
Efficiency	NPV per amount remediated (SEK/tonne)	-	-	851	993	152
Efficiency	Cost per amount remediated (SEK/tonne)	-	-	2414	2267	2026
Efficiency	Cost per environmental risk reduction (MSEK/score)	21.5	41.0	38.6	36.3	40.8
Efficiency	Cost per human health risk reduction (MSEK/score)	61.9	53.8	46.7	43.8	57.7

6.4 Combined Analysis

A combination of the result from Paper I and Paper II is shown in Table 6-7. It shows how the top ranked alternative resulting from the different assessment scenarios (Paper I) perform on the effectiveness and efficiency indicators (Paper II), respectively. The table shows the number of times the top alternative outcome from each scenario ranked highest on the studied indicators.

The full SCORE assessment, resulting in an alternative which is most sustainable, had the most number of indicator “wins” in one of four case studies, the Limhamn case, obtained from the efficiency indicators.

Both the private scenarios resulted in two case studies with the most number of indicator wins, Hexion and Limhamn. These alternatives performed better with respect to the efficiency indicators. This is a result of the high economic weighting in these scenarios, meaning that the top alternatives typically had the lowest cost or highest NPVs. For the BT Kemi case, six of the efficiency indicators were not quantified for BT1 and BT2. If only BT3 – BT5 are compared on these indicators, either BT4 or BT5 performed best overall, and these alternatives either had the lowest cost (BT4) or was most extensive (BT5).

The Public-Traditional scenario, which was seen to result in the most extensive and expensive remediation alternatives, had the most number of indicator wins in the Järpen and BT Kemi cases. In these two cases, it is seen that the indicator wins come primarily from effectiveness indicators, as a result of alternatives which were extensive in soil removal. The Public-Green scenario resulted in the most number of indicator wins in the Järpen, Limhamn, and BT Kemi cases, typically favouring the most extensive alternatives and thus the effectiveness indicators.

Table 6-7. Combined analysis showing the number of effectiveness/efficiency indicators where the best alternative outcome from the different scenarios, shown in parentheses, performs best. The scenarios resulting in alternatives performing best on the most number of indicators, for a given case study, are marked in bold.

	Number of effectiveness/efficiency indicator “wins” by top alternative from each scenario				
	Full SCORE	Private-Traditional	Private-Green	Public-Traditional	Public-Green
Hexion	2 / 0 (Alt. H4)	**1 / 7** (Alt. H3)	**1 / 7** (Alt. H3)	3 / 2 (Alt. H1)	2 / 0 (Alt. H4)
Järpen	0 / 2 (Alt. J4)	0 / 3 (Alt. J3)	0 / 2 (Alt. J4)	**5 / 0** (Alt. J5)	**5 / 0** (Alt. J5)
Limhamn	**2 / 5** (Alt. L4)	**2 / 5** (Alt. L4)	**2 / 5** (Alt. L4)	3 / 1 (Alt. L2)	**2 / 5** (Alt. L4)
BT Kemi	3 / 1 (Alt. BT4)	3 / 1 (Alt. BT4)	3 / 1 (Alt. BT4)	**5 / 0** (Alt. BT5)	**5 / 0** (Alt. BT5)

7 DISCUSSION

A summary of the key discussion points from the literature review and Paper I and II are provided in this section. In addition, discussion on the results of the combined analysis of Paper I and II is given.

7.1 Efficient and Effective Remediation

A first step in reaching the aim of this thesis was to investigate how efficiency and effectiveness, essentially encompassing the single Swedish word "*effektivitet*", are considered with respect to contaminated site remediation. It was found that the terms are used on three different levels: technical, project and national. The technical level, where thousands of studies have been performed on the efficiency and effectiveness of remediation techniques and methods, was deemed to not be relevant to the aim of the work, though it is acknowledged that the technical level feeds into efficiency and effectiveness on the project and national levels. The project level, concerning the efficiency and effectiveness of projects, typically measured by indicators, is of greatest focus in this work, as it relates to the assessment of remediation project alternatives.

Literature on project efficiency and effectiveness is scarce. Two Swedish studies, comparing the efficiency and effectiveness of publicly funded projects (inter-project), provided the majority of relevant indicators. These studies considered efficiency and effectiveness mainly in terms of time, costs, amounts removed, as well as some wider social and environmental aspects. A lack of indicators was found which related to risk reduction and site specific goals. The indicators could be divided and classified into efficiency and effectiveness categories based on their definitions as well as the descriptions provided by Zidane & Olsson (2017). It should be stated that the division of some indicators, such as remediation time and costs, was difficult. Time and costs were considered as efficiency indicators amongst the other time and cost ratio indicators. The ratio indicators, provide the best possibility of comparing projects of different size, though it remains difficult to compare sites with differing contamination situations, complexities, and problem owners.

7.2 Scenario Analysis

The scenario analysis performed in Paper II generally shows that assessment views, other than a full sustainability approach, produce different rankings of alternatives, thus potentially leading to different decision outcomes. It is seen that full sustainability assessment, considering all criteria and indicators, and with equal weighting to the environmental, social, and economic dimensions, result in alternatives which best balance positive and negative effects. The constructed assessment scenarios tend to miss important aspects and differences between alternatives that a full sustainability view accounts for.

The Public-Traditional scenario, with low economic dimension weighting and without consideration of secondary environmental regional or global effects, prioritizes the most extensive options. The scenario reflects the common risk management approach taken from the 1970's to 1990's. Although guidelines exist today which require that at least some social indicators are considered in publicly funded projects (SEPA, 2009), it is a concern that this assessment view potentially leads to alternatives with high costs and large environmental footprints.

The private scenarios, reflecting the perspective of a private owner, with high economic dimension weighting, favour the least expensive remediation alternatives. The constructed scenarios, considering only increased property values (B1) and remediation costs (C1), miss out on economic externalities that a full economic assessment (CBA) considers. This greatly affected the results compared with the full sustainability view. For example, in the BT Kemi case, the four assessment scenarios fail to account for positive externalities relating to increased property values in the surrounding as a result of the reduction of source contamination and the long-term stigma of the site. Not including benefits or externalities may give a misleading picture of the costs in relation to benefits for a project. However, even with inclusion and monetization of externalities, human health and environmental effects which are not economic in nature must be addressed in the other sustainability dimensions.

Sustainability assessment allows for the possibility to formalize the inclusion of all aspects of a decision situation, doing so in a transparent manner. The analysis illustrates that the alternate scenarios, and other assessment approaches, miss important aspects that may be very relevant for the decision situation. The decision outcomes are seen to be sensitive, highlighting the importance of including uncertainty analysis and documented motivation of stakeholder values and perspectives.

7.3 Efficiency and Effectiveness Analysis

The list of selected general efficiency and effectiveness indicators is seen to stem from a "dig and dump" mind-set, pertaining mostly to time, costs, and amounts removed. In the BT Kemi case, with two in-situ alternatives, comparison with the excavation and disposal alternatives on several indicators was difficult. In addition, several indicators, such as cost and NPV, seem to "double count" aspects. This arises when externalities, both positive and negative, are considered to a limited extent, and when benefits are equal amongst alternatives. In the Hexion case however, where both positive and negative externalities have a bigger impact, interesting differences in the indicator results are seen, such as how the most extensive alternative performs best with respective to cost per amount remediated but worst with respect to NPV per amount remediated. The double counting becomes an issue when looking at the number of indicators that the alternatives perform best on overall.

All of the studied efficiency indicators consider time or costs in some way, though risk reduction and economic externalities are also included. Only four effectiveness indicators, emissions, clean soil for refilling, and human health and environmental risk reduction, could be said to consider wider social and environmental aspects. An apparent imbalance in indicators found in literature is therefore seen. In the Järpen case, for example, alternative J4 which was assessed to be the most sustainable alternative, performs poorly on most efficiency indicators. It ranks highest, however, on cost per human health risk reduction and cost per environmental risk reduction, two indicators combining aspects which are deemed very important, and which are not necessarily excavation and disposal focused. The performance of indicators on the list of general indicators does not consider the importance of aspects or the views and perspectives of stakeholders.

Looking across all case studies, it is seen that the most sustainable alternative does not generally lead to the most efficient or effective remediation according to the list of indicators. This is likely due to the fact that the general list of indicators lacks wider social and environmental aspects. There is no indicator which relates to the most sustainable alternative over all cases, though cost per human health and environmental risk reduction, NPV, and emissions relate most. Sustainability assessment, considering a wide array of criteria, typically shows the best balance of contrasting aspects. It is clear, however, that the most extensive alternatives generally perform best on the effectiveness indicators and that the least expensive alternatives perform best on the efficiency indicators.

The case-specific indicators from group interviews for the Järpen and BT Kemi sites, relating to case-specific goals, can mostly be said to be effectiveness indicators. In general, they relate better than the general indicators to sustainability, though this is not that surprising as remediation goals could be thought to be typically formulated to include broader social effects. In the Järpen case, the indicators do not account for balancing of negative secondary effects, favouring simply the most extensive alternative. The case-specific goals and indicators for the BT Kemi case, however, better show the trade-off between maximizing contaminant removal and minimizing secondary local and global effects.

As sustainable development continues to receive increased focus worldwide, it could be expected that guidelines will require more sustainability aspects to be considered in the assessment of contaminated site remediation projects. Assuming that wider social and environmental criteria and economic externalities are considered on an intra-project level, then ratio indicators pertaining to time and costs could prove useful inter-project, potentially leading to cost-effective prioritization and better progress of national remediation programs. This would however require that clear definition of efficiency and effectiveness of remediation projects is given on a policy level.

7.4 Combined Analysis of Paper I and II

As was expected, the private scenarios result in low-cost alternatives and seem to perform well with respect to efficiency indicators. The public scenarios on the other hand, with the most extensive and expensive remediation alternatives, perform well with respect to effectiveness indicators but less so with respect to efficiency indicators (time and costs).

A potential bias in the results of the sustainability assessments is seen from the combined analysis table. The best alternatives in the private scenarios, result in the most wins for the Hexion and Limhamn cases, performing well due to high NPVs and low costs. However, the Hexion and Limhamn cases are private exploitation projects, and therefore the issue of bias in performing the sustainability assessment is raised. This bias could also be said to be seen in the public scenarios together with the public projects (Järpen, BT Kemi), resulting I extensive alternatives. Though the SCORE assessments were attempted to be done as objectively as possible, the bias could arise in the selection of alternatives to be assessed a well as the weighting and scoring of criteria and indicators.

Given the imbalance of the efficiency indicators, which pertain exclusively to time and cost aspects, it is quite obvious that the scenarios which favour the more extensive or cheaper alternatives perform well on more indicators. It should be recalled though that sustainability assessment may best balance all indicators. Performing a statistical correlation analysis to investigate this hypothesis would be of interest for further study. Also, had the indicators included a greater number of wider social, environmental and risk reduction aspects, the results might have been vastly different.

The combination table shows that a full sustainability view leads to the most number of efficiency and effectiveness wins in only the Limhamn case. The Public-Traditional view was seen from the scenario analysis to lead to most extensive and expensive outcomes, thereby performing well with respect to the effectiveness indicators. The Public-Traditional assessment view is that which reflects how publicly funded remediation has previously been conducted in Sweden. While the Public-Traditional view is effective in terms of the extent of remediation, it could be expected that a full sustainability view would have led to less expensive projects, and a higher number of site clean-ups completed, all the while considering a broader set of effects on society and the environment.

8 CONCLUSIONS

The main conclusions from the thesis are:

- The use of efficiency and effectiveness with respect to contaminated site remediation in literature can be conceptualized on three levels: Technical, Project, and National. Further, indicators found in literature can be categorized as efficiency or effectiveness indicators, depending on whether focus is on productivity in terms of outputs vs inputs (efficiency), or on reaching specified goals or outcomes (effectiveness).

- Literature on efficiency and effectiveness, in the context of contaminated site remediation, is mainly focused on time, costs, and amounts remediated, and to a lesser extent on wider social and environmental aspects. A lack of efficiency and effectiveness indicators related to risk reduction and project specific goals was found.

- Comparison of cases differing in problem owner, site complexities, and with different remediation alternatives is difficult. However, it is generally seen that applying a full sustainability assessment can result in a decision support outcome that is different in terms of remediation extent, costs, and remediation technology than what is supported by more limited decision support approaches for evaluating alternatives.

- Sustainability assessments are seen to often result in decision support outcomes that balance trade-offs, the “middle of the road” approach. Additionally, full sustainability assessment offers the opportunity to account for all relevant factors, including soft social aspects, in a structured way, which may ultimately be very important for the end decision in a project.

- The Public-Traditional view tends to consistently result in the most extensive and expensive remediation alternatives, while the private perspective typically ranks the low-cost alternatives highest. Inclusion of positive economic externalities may, at least in urban areas, balance the often large costs associated with remediation.

- Efficiency and effectiveness indicators found in literature pertain primarily to time, costs, and amounts, which do not strongly support sustainable remediation. Case-specific indicators, determined through group interviews with project teams, are seen to relate better with sustainability assessment. Use of indicators to assess site remediation should include wider environmental and social aspects as well as economic externalities.

- The effectiveness indicators generally favour the most extensive alternatives, while the efficiency indicators generally favour the low-cost alternatives.

- Time and cost related efficiency indicators may be more applicable in comparing different projects (inter-project) than comparing alternatives within a project (intra-project). Clear definitions of efficiency and effectiveness needs to be given on a policy level in order to reach greater efficiency and effectiveness of remediation of publicly funded sites nationally.

- The combined analysis shows that the outcomes of the alternate assessment scenarios rank higher on more effectiveness and efficiency indicators than the full sustainability assessment scenarios. Not surprisingly, the public perspective scenarios, resulting in extensive alternatives, perform well on the effectiveness indicators. The private perspective scenarios, resulting in low-cost alternatives perform well with respect to efficiency indicators.

- The Public-Traditional scenario, reflecting how projects have previously been assessed in Sweden, are seen to be effective in certain cases due to extensive contaminant removal. Compared to this scenario, a full sustainability assessment, balancing trade-offs between a broad consideration of effects, would likely lead to less expensive projects and a better rate of site completions within a given budget.

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