# Sustainability Assessment of In-Situ Remediation Techniques Using the SCORE Method

The Kolkajen-Ropsten Case Study

Master's thesis in the Nordic Master's Program Environmental Engineering

LUCA FRANCESCHINI

Department of Civil and Environmental Engineering
Division of Geology and Geotechnics
CHALMERS UNIVERSITY OF TECHNOLOGY
Gothenburg, Sweden 2018

DTU Environment
TECHNICAL UNIVERSITY OF DENMARK
Lyngby, Denmark 2018

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Supervisor: Jenny Norrman, Architecture and Civil Engineering (Chalmers)
Co-Supervisor: Gitte Lemming Søndergaard, DTU Environment (DTU)
Co-Supervisor: Poul Løgstrup Bjerg, DTU Environment (DTU)
Examiner: Lars Rosén, Architecture and Civil Engineering (Chalmers)

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Department of Architecture and Civil Engineering
Chalmers University of Technology
SE-412 96 Gothenburg
Telephone +46 31 772 1000

DTU Environment
Denmark Technical University
Bygningstorvet, Bygning 115, 2800 Kgs. Lyngby
Telephone + 45 25 16 00

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DTU Environment
Denmark Technical University

# Abstract

In Sweden, approximately 80 000 potentially or confirmed contaminated areas are present, with the environmental protection agency (SEPA) concerned about the slow progress of remediation and the wide use of the traditional excavation and landfilling of the contaminated soil method instead of innovative in-situ techniques. Therefore, in the last years sustainability played an increasing role when designing remediation techniques. In order to provide a transparent assessment of the sustainability of different remediation alternatives for a site, the SCORE method was developed by Rosén, et al., 2015.

In this thesis, a way to include the assessment of in-situ techniques in the SCORE framework was implemented: this has been done identifying the main causes of environmental impacts for the remediation techniques considered and creating accordingly new subcriteria in the environmental domain, scored using the MCDA (multi-criteria decision analysis) tool Web-HIPRE. The subcriteria regarding the effects of the remediation on soil, groundwater and surface water were scored semi-quantitatively with information from literature. The subcriteria regarding the effects on air and non-renewable natural resources were scored using the output of a streamlined life-cycle assessment (LCA) performed with SimaPro.

This improved framework was tested on the case-study of Kolkajen-Ropsten site, a former industrial port with heavy PAH contamination in the soil and groundwater, planned to be redeveloped. The actual assessment was based on a conceptualized site, due to inherent difficulties and data unavailability at the time this work was carried out. Five alternatives consisting of different ex-situ and in-situ techniques coupled together were compared: excavation of 5 meters of soil coupled with in-situ chemical oxidation (ISCO), excavation of 1 meter of soil followed by stabilization/solidification (S/S) and then followed by ISCO, excavation of 5 meters of soil followed by bioremediation, excavation of 1 meter of soil followed by S/S and then bioremediation and excavation of 5 meters of soil followed by in-situ thermal stabilization. In the sustainability assessment, composed by assessments on the environmental, social and economic domains, the techniques involving the least amount of soil excavated and landfilled obtained the highest score, with the choice of which one to select that was discussed to be dependent also on other factors, such as budget and time constraints.

Keywords: contaminated sites, sustainability assessment, multi-criteria decision analysis, cost-benefit analysis, streamlined life-cycle assessment, in-situ remediation techniques, SCORE method

# Preface and acknowledgments

The present thesis represents the final step to obtain my Master of Science degree in the joint Nordic Master's Program in Environmental Engineering at Denmark Technical University and Chalmers University of Technology. The project was carried out under the supervision of Associate Professor Jenny Norrman (Chalmers), Senior Researcher Gitte Lemming Søndergaard (DTU) and Professor Poul Løgstrup Bjerg (DTU) at Chalmers University of Technology, Division of Geology and Geotechnics of the Department of Architecture and Civil Engineering, from January to June 2018.

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Göteborg, June 2018.

Luca Franceschini

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## List of Abbreviations

AHP = Analytical Hierarchy Process
AS = All scores possible
b.g.l. = below ground level
B = Beneficiary
BTEX = Benzene, Toluene, Ethylbenzene, Xylene
CCEE = Canadian Council of Ministers of the Environment
CBA = Cost-Benefit Analysis
DEV = Developer
DNAPL = Dense Non-Aqueous Phase Liquids
EEA = European Environmental Agency
e.g. = exempli gratia (‘for example’)
EMP = Employees
ERH = Electrical Resistance Heating
FRTR = Federal Remediation Technologies Roundtable
H = High importance
i.e. = id est
ILCR = Incremental Lifetime Cancer Risk
ISCO = In-Situ Chemical Oxidation
ISO = International Standard Organization
ISTD = In-Situ Thermal Desorption
ISTS = In-Situ Thermal Solidification
kr = Swedish krona (currency)
L = Low importance
LCA = Life Cycle Assessment
LCI = Life Cycle Impacts or Life Cycle Inventory
LCIA = Life Cycle Impacts Assessment
LCL = Lower Confidence Level
LEQ = Local Environment Quality
M= Medium importance
MAUT/MAVT = Multi-Attribute Utility/Value Theory
MCA = Multi-Criteria Analysis
MCDA = Multi-Criteria Decision Analysis
MCL = Maximum Contaminant Level
MLV = Most Likely Value
MSEK = million Swedish kroner
NAPL = Non-Aqueous Phase Liquid
NICOLE = Network for Industrially Contaminated Land in Europe
NIOSH = (US) National Institute for Occupational Safety and Health
NN = No negative score possible
NP = No positive score possible
NPV = Net Present Value
NR = Not relevant
ORC = Oxygen Releasing Compound
P = Payer
PAH = Polycyclic Aromatic Hydrocarbons
PAH L = Light molecular weight PAH
PAH M = Medium molecular weight PAH
PAH H = Heavy molecular weight PAH

PCB = Polychlorinated Biphenyl
PRB = Permeable Reactive Barrier
PUB = Public
PV = Present Value
RA = Remedial Action
S = Score
SC = Source of Contamination
SCORE = Sustainable Choice Of REmediation
SEE = Steam Enhanced Extraction
SEPA = Swedish Environmental Protection Agency
SGI = Swedish Geotechnical Institute
SGU = Sveriges Geologiska Undersökning (Geological Survey of Sweden)
S/S = Solidification/Stabilization
TCH = Thermal Conductive Heating
TEFPR = Thermally Enhanced Free Product Recovery
U = Uncertainty
UCL = Upper Confidence Level
USEPA = United States Environmental Protection Agency
WDNR = Wisconsin Department of Natural Resources
Web-HIPRE = HIerarchical PREference analysis on the World Wide Web
WWTP = Wastewater Treatment Plant

# 1. Introduction

## 1.1. Background

The Swedish Environmental Protection Agency (SEPA) and the Geological Survey of Sweden (SGU) estimate that approximately 80 000 potentially or confirmed contaminated areas are present in Sweden, of which 1 300 are heavily contaminated sites (SGU, 2017). SEPA is concerned that, due to the slow progress of remediation and the fact that the traditional excavation followed by landfilling of contaminated soil method is still the most used technique (SEPA, 2006), the national objective ‘A Non-Toxic Environment’ may not be reached (SEPA, 2012). There is also concern that remediation of these sites will be too expensive and that the level of technological innovation is low, with the vast majority of remediation projects being performed by excavation and disposal off-site.
Due to the fact that application of more innovative techniques, including in-situ methods, is limited (Common Forum EU, 2014), the Swedish Government has appointed the Swedish Geotechnical Institute (SGI) to take responsibility for research and development, in order to increase the efficiency of the nationally funded remediation program and to reach environmental objectives. In the annual national stakeholder survey by SGI, identification, design and selection of remediation alternatives are repeatedly specified as the most important issues to develop and improve to increase efficiency (SGI, 2011).

Remediation of contaminated sites has both positive and negative aspects: it is useful and necessary to reduce the negative effects of the contaminants on human health and ecosystem, it improves recreational use of the site and it can create new jobs, but site remediation itself may result in significant environmental footprints, high cost and low social acceptance (Kuppusamy, et al., 2016). In Sweden, excavation/landfilling method still dominates among the applied remediation techniques. To avoid shifting the problem from an environmental matrix to another, for instance remediating the soil but generating high amounts of problematic air emissions, or to move the problem from one place to another, such as remediating a contaminated site by moving the contaminated soil to another area, the concept of ‘sustainable remediation’ has gained interest. The concept of sustainability, applied to remediation, aims to provide benefits on as many aspects as possible, in the three macro areas of environmental, social and economic aspects (Bardos, 2014). In order to incorporate sustainability in the decision-making procedure, a number of methods and tools have been developed for assessing the sustainability in remediation projects, based on e.g. multi-criteria decision analysis (MCA/MCDA) and life-cycle assessment (LCA).

SCORE (Sustainable Choice Of REmediation), which is a multi-criteria decision assessment tool developed by Rosén et al., (2015), has been applied with this purpose to a number of sites, but yet there is little experience of application to sites with in-situ remediation technologies (Rosén, et al., 2015; Anderson, et al., 2018).

## 1.2. Aim

The overall aim of the project is to evaluate the sustainability performance of remediation methods involving innovative in-situ techniques combined with varying degree of excavation, using the SCORE method. The sustainability assessment is done for a number of different in-situ remediation options at the Kolkajen-Ropsten site in Stockholm. The novelty of this study is (1) the development of a methodology to assess in-situ remediation techniques within the SCORE method, and (2) elaborating further on the environmental criteria through the application of a streamlined life-cycle assessment.

## 1.3. Limitations

Five techniques involving in-situ techniques together with ex-situ techniques are investigated and analysed with the SCORE method. The in-situ techniques are chosen amongst a number of in-situ methods identified in the Kolkajen project and implemented as pilot tests on the site, therefore other techniques that might be appropriate for the site are not evaluated within this study. The quantification of the environmental, social and economic effects of the different alternatives is based on the reports produced in the remediation project and scientific literature, but not by engaging different stakeholders in a structured way. The uncertainties associated with the quantification of the effects are treated with a Monte-Carlo simulation approach (Rosén et al., 2015). Only rather straightforward economic valuation methods are used, where there are data available, e.g. CO2-emissions and human health valuation, but more complex valuation methods are not possible to perform within the scope of the Master's thesis project.

Some limitations are also present due to the complex geology of the site: the bedrock differed from approximately 5 meters below ground level (b.g.l.) to approximately 20 meters b.g.l., thus some simplifications and assumptions are required when modelling the site. Finally, the size of the site to be remediated is not clearly defined at the time this project is carried out.

# 2. Remediation and management of contaminated sites

The purpose of contaminated sites management is to reduce the negative impacts of contaminated sites to a tolerable level, according to the regulations on the matter: the level is defined acceptable when the concentration of contaminants is lower than the level that gives undesired health or environmental effects (Panagos, et al., 2013). A site is defined as ‘contaminated’ when the presence of contamination has been confirmed and there is a potential risk to humans, water, ecosystems or other receptors, while it is defined ‘potentially contaminated’ when contamination above the limits is suspected but not yet verified, and therefore more information is needed (Panagos, et al., 2013). Depending on the severity of the contamination, risk reducing measures might be needed, such as remedial actions.

## 2.1. Sustainable remediation

The contradictory effects of remediation have received increased attention over the last decade. A number of strategies and programs have been developed taking a more holistic view on remediation in order to provide for more sustainable remediation, such as:

- The USEPA Green Remediation program (USEPA, 2012), that was launched to establish relevant metrics and a methodology for evaluating the environmental footprint of remedial actions.
- The Sustainable Remediation Forum in the UK (SuRF, 2010) and the Network for Industrially Contaminated Land in Europe (NICOLE, 2012) suggested frameworks and indicators for comprehensive sustainability evaluation of remedial actions, considering positive and negative environmental, economic and social effects.
- The International Standard Organization has recently published on a standard on sustainability assessment of remedial actions (ISO, 2017).

Being now widely recognized as an important part of the remediation process, a number of tools and methods based on multi-criteria analysis or life-cycle assessments has been developed to support sustainability assessments of remedial techniques.

## 2.2. Environmental impacts of remediation projects

When talking about environmental impacts of remediation, a distinction can be made between primary, secondary and tertiary impacts (Sparrevik, et al., 2011). Human toxicity, ecotoxicity and all the environmental impacts caused by the on-site contamination are the primary impacts, the environmental impacts due to the remediation activity are the secondary impacts and the environmental impacts associated with the future use of the site are the tertiary impacts (Lesage, et al., 2007). It has to be considered that the environmental impacts are not present only on-site, but also on a local, regional and (sometimes) global scale, because the emissions take place during different life stages of the remediation and thus in different geographical locations (Lemming & Owsianiak, 2018).

When assessing the environmental impacts, it is important to understand what are their main drivers. Regarding the primary impacts, the effects of the contaminants on the ecosystem are the most important, hence site-specific models are needed (Lemming & Owsianiak, 2018). For the secondary impacts electricity, energy use, material use for installations and chemicals used (if any) are the main ones on-site for in-situ technologies, while production and transport of the different chemicals are the main ones off-site (Cadotte et al., 20017; Lemming et al., 2012), with transport processes having a great impact for ex-situ remediation techniques as well (Lemming & Owsianiak, 2018). Moreover, energy use and the amount of land used for the remediation are two parameters that can greatly influence the outcomes of impact assessments. In general, energy-intensive methods are usually faster than less energy-intensive techniques, and it is therefore important to define the importance that impacts on land use or impacts of energy requirements have on the overall assessment (Lemming & Owsianiak, 2018). The assessment of tertiary impacts is not always clear, since it requires information on the future use of the land (Lemming & Owsianiak, 2018), but it is less of a problem for projects regarding sites where the future use is already determined.

## 2.3. Multi-Criteria Analysis

Environmental decisions often require multidisciplinary knowledge bases, such as natural sciences, physics, social sciences, medicine, ethics and also politics. Therefore, when addressing environmental problems, it is important to be able to consider all these different facts. Multi-criteria analysis (MCA) and multi-criteria decision analysis (MCDA) are a good way to address complex and multifaceted situations through a systematic analysis in order to aid the decision-making process, with the possibility to include stakeholders' views about the different projects analysed in the decision-making process, and making it as transparent as possible (UK Treasury, 2009). The term multi-criteria decision analysis is sometimes adopted when numerical values are used for scoring the different criteria (Rosén, et al., 2015). The four principal MCDA approaches, described in Linkov, et al., 2004, are: (1) elementary methods, that aims to reduce complex problems to a singular basis, in order to select a preferred, or best, alternative, (2) multi-attribute utility/value theory (MAUT/MAVT), a technique that aims to express in a simple way the decision-makers' preferences, (3) analytical hierarchy process (AHP), a quantitative comparative based on pair-wise comparisons and a linear additive model, and (4) outranking, a partially compensatory method that does not rely on optimization, based on the principle that one alternative is more important over another, comparing the alternatives in pairs and obtaining as a result a ranking of the different alternatives.

MCA is often used to assess how much a project or solution fulfils a set of performance criteria (Rosén, et al., 2015), because using MCA it is possible to integrate different types of qualitative and quantitative information into a broad evaluation. MCDA is increasingly used to provide support in environmental decision-making and for sustainability appraisal (Belton & Stewart, 2002; Burgman, 2005) and it has been suggested for sustainability evaluation of remedial actions by a number of authors, such as Rosén, et al., 2009, Harbottle, et al., 2011, Linkov & Moberg, 2012, Lemming, et al., 2017. However, some drawbacks have been observed when using MCA/MCDA methods, such as double-counting due to overlapping of criteria, system boundaries not clearly defined, lack of uncertainties analysis and unclear definitions of performance scales (Rosén, et al., 2015).

## 2.4. Cost-Benefit Analysis

In order to take into consideration also the economic aspects of the remedial options, cost-benefit analyses (CBA) can be performed (Söderqvist, et al., 2015). Usually, CBA has a common structure, as described in (Hanley & Spash, 1993): (1) definition of the project, where it is defined the reallocation of the resources being proposed and the population over which costs and benefits are to be aggregated, (2) identification of project impacts, where all the impacts resulting from the implementation of the project have to be identified, (3) definition of those impacts that are economically relevant, among which it is important to count for the externalities, (4) quantification of the relevant impacts, (5) monetary valuation of relevant effects, where it is important to keep in mind that future prices may change, (6) discounting of cost and benefit flows, necessary to convert all the monetary amounts into present value (PV) terms, (7) calculation of the NPV, as described in equation 3 and (8) sensitivity analysis, needed because the evaluation of some environmental aspects cannot be precise by definition (valuation of non-market goods, ecosystem complexity and discounting are some of the main reasons for the imprecision).

To perform a proper CBA, it is important to define which costs and benefits are to be included, how they are evaluated, at what interest rate future benefits and costs are to be discounted to obtain the present value and what are the relevant constraints (Brent, 1996), and how these objects are defined depends on the stakeholders involved and on whose welfare is to be maximized (Brent, 1996). The choice of the discount rate is fundamental to calculate the NPV, paramount to determine the fate of a project (Brent, 1996). In Sweden, the discount rate for infrastructure projects is set to 3.5-4%, even if the choice of the proper value for this parameter is still debated (Nordlöf, 2014).

## 2.5. Life-Cycle Assessment

LCA has also been included for the assessment of environmental impacts within a sustainability assessment (Lemming, et al., 2013), and it is increasingly used in contaminated sites management. LCA has also been used as a tool to provide decision-support on the choice of which remediation technology to use, because it takes a life cycle perspective, allowing to identify and prevent eventual new environmental impacts that could arise modifying one stage of the life of a system and to cover a broad range of environmental issues, with the aim of avoiding burden shifting (Bjørn, et al., 2018a). It is a quantitative analysis, and it can be used to compare environmental impacts of different processes and products. The principles and frameworks of LCA are described in the standard ISO 14040 and ISO 14044 (ISO 14040, 2006; ISO 14044, 2006). While the main goal of LCA studies is often to decide which alternative is the preferable from an environmental point of view or where are the greatest environmental impacts in the life cycle of a product, life cycle impacts assessment (LCIA) studies can aid the interpretation showing the system's impact on a number of different categories (Hauschild & Huijbregts, 2015). ISO 14040 describes the necessary steps for the LCIA phase (ISO 14040, 2006).

As described in ISO 14040 and ISO 14044, LCA studies usually consists of four steps: (1) definition of the goal and scope of the study, (2) collection of all the environmental inputs and outputs of the product (life cycle inventory, LCI), (3) assessment of the environmental relevance of the inputs and outputs (life cycle impact assessment, LCIA) and (4) interpretation of the study.

## 2.6. Remediation techniques

Contaminated sites can be remediated using techniques that involve the extraction and/or excavation of the contaminated soil and groundwater, and techniques that target the contamination in the subsurface, without the removal of the polluted matrix. The firsts are the so-called ex-situ techniques, the latter are defined as in-situ techniques (Lemming & Owsianiak, 2018). It is not rare to use a combination of different techniques, such as shallow excavation followed by the use of in-situ techniques in the deeper soil.

### 2.6.1. Ex-situ remediation techniques

Ex-situ remediation techniques always involve physical extraction of the contaminated media to the surface for treatment. The treatment can be done at the site (on-site) or at another location (off-site) (Kuppusamy, et al., 2016). If the pollutants are present only in the soil, the soil is usually excavated and either treated or disposed, when the contaminants are present in the groundwater, it is pumped and treated above ground, where it is often treated on-site in a pump-and-treat facility (Kuppusamy, et al., 2016). Common ex-situ on-site remediation techniques are pump-and-treat, thermal treatment, biopile, chemical oxidation, soil washing, bioremediation and solidification/stabilization, common ex-situ off-site techniques are pump-and-treat (with the transport of the contaminated media to a water treatment plant off-site), incineration (with the transport of the contaminated media to a incineration plant off-site) and the most common ex-situ off-site technique is the excavation of the contaminated soil and disposal in landfills or engineered landfills, also known as dig-and-dump (Kuppusamy, et al., 2016; Lemming & Owsianiak, 2018).

*Excavation followed by landfill disposal of the contaminated soil method*
In order to remove the contamination from the site, polluted soil can be excavated and then disposed at a landfill (traditional 'dig and dump' method). Landfilling is the oldest way to handle waste, where materials are buried or disposed in a designated site (Kuppusamy, et al., 2016). However, in the last years, this remediation method has become less attractive due to the EU directive on landfills, that banned the disposal of non-hazardous and hazardous wastes together (The Council of the European Union, 1999) and due to the increasing interest in the use of more sustainable remediation alternatives (Bardos, et al., 2010), a requisite not always fulfilled by landfills (Allen, 2001; Harbottle, et al., 2007).

Excavation followed by landfill disposal is often a quick and simple method, but it has many drawbacks: from a social and economic point of view, excavation/landfilling method is linked with high costs and significant production of dust and noise on-site (Kuppusamy, et al., 2016; Anderson, 2017) and with low social acceptance of landfills when close to residential areas or drinking water sources (Sasao, 2004). Moreover, this method has negative environmental effects, such as large emissions of greenhouse gases due to the transport, use of non-renewable resources, waste production and eventual further contamination from the landfill itself (Kuppusamy, et al., 2016; Anderson, 2017). In case of deep excavation, it may be necessary to use retaining walls to support the mass of soil laterally that otherwise would not naturally keep to: sheet piling is a common way to do that in soft soils. Sheet piles are long walls with a vertical interlocking system that are driven into the soil, and they can be permanent or temporary, depending if they are used as permanent retaining structures or just to provide safe access to the site for construction and then being removed.

### 2.6.2. In-situ remediation techniques

With the use of in-situ remediation techniques, the contaminants are treated on site and without prior physical extraction of the contaminated media. The use of these techniques usually has a lower cost than the classic excavation/landfilling method, but it can be less effective and slower (Kuppusamy, et al., 2016). Common in-situ techniques are phytoremediation, bioremediation, in-situ chemical oxidation (ISCO), permeable reactive barrier (PRB), thermally enhanced remediation and soil flushing (Lemming & Owsianiak, 2018).
Only the techniques relevant for the thesis will be further described.

*In-situ chemical oxidation*
In Situ Chemical Oxidation (ISCO) is a remediation technique that implies the introduction of strong oxidants in the subsurface in order to react with the contaminants (Siegrist, et al., 2014). The most commonly used reagents are hydrogen peroxide and catalysed hydrogen peroxide (CHP), ozone, permanganate, persulfate and activated persulfate, or combinations of oxidants such as hydrogen peroxide and sodium persulfate or ozone and hydrogen peroxide (Siegrist, et al., 2014).
Hydrogen peroxide ($H_2O_2$) is a strong oxidant with the potential to oxidize many organic compounds, but the slow reaction kinetics make it sometimes ineffective (Siegrist, et al., 2014). If applied with a catalyst, $H_2O_2$ can yield hydroxyl radicals ($HO^\bullet$), in a reaction that is commonly known as Fenton oxidation (Innocenti, et al., 2014), that is shown in equation 1.

$$H_2O_2 + Fe^{2+} \rightarrow OH^- + OH^\bullet + Fe^{3+} \qquad \text{Eq. 1}$$

Peroxydisulfate ($S_2O_8^{2-}$), commonly referred to as persulfate or persulfate ion, is an emerging oxidant used in the last decade as an alternative oxidant for the degradation of organic pollutants (Albergaria & Nouws, 2016; Tsitonaki, et al., 2010). Persulfate salts dissociate in water to form persulfate anions, which is a strong and stable oxidant, as shown in equation 2.

$$S_2O_8^{2-} + 2e^- \rightarrow 2SO_4^{2-} \qquad \text{Eq. 2}$$

The usual forms of persulfate that occurs in ISCO applications are sodium, potassium or ammonium salts, but the most used is sodium persulfate, due to its higher water solubility and benign residual products (Tsitonaki, et al., 2010). However, persulfate reacts more slowly than other oxidants, thus various agents are used to activate it, such as heat, UV, high pH, $H_2O_2$ and transition metals (usually $Fe^{2+}$) (Albergaria & Nouws, 2016), and is seldom used without a catalyst or an activator (Ranc, et al., 2016).

Sulphate radicals are highly reactive and have a short lifespan and the rate of reaction can be influenced by the presence of electron-donating or electron-withdrawing groups. The first ones (such as amino, hydroxyl or alkoxy groups) increase the reaction rate of persulfate with the contaminants, the latter (such as nitro or carbonyl groups) decrease it (Tsitonaki, et al., 2010). Once the sulphate radical is present, it can contribute to the formation of the hydroxyl radical, as shown in equation 3, which can enhance the decomposition of the contaminants (Tsitonaki, et al., 2010)

$$SO_4^{\bullet-} + OH^- \rightarrow OH^\bullet + SO_4^{2-} \qquad \text{Eq. 3}$$

Some issues are related with the use of peroxide and persulfate in ISCO applications, one of the main drawbacks is that some of the by-products of ISCO might be incompatible with aquifer physical or chemical characteristics. The groundwater can be influenced by the fact that oxidation reactions can make metals more mobile and more toxic, some oxidant formulations may have impurities and the different oxidants can change the pH of the subsurface, influencing also the groundwater (low pH with $H_2O_2$, high pH with sodium persulfate) (Siegrist, et al., 2014). Other issues can be related to the clogging of the filters that provide the chemicals due to formation of reaction products and particles, and also related to the reduction of the subsurface permeability. Also, oxidation in the treatment zone can perturb ambient microbial ecology and disrupt biomass levels, but the effects are usually short term (Siegrist, et al., 2014). One of the main issues when dealing with PAH-contaminated soils is the determination of the optimal doses of reagents in the injected solutions (Ranc, et al., 2016).

### *Bioremediation*

Bioremediation is widely recognized as an efficient way to clean-up petroleum hydrocarbons contaminated soils (Okoh, 2006), where naturally occurring microbial population in the site is used to degrade the contaminants. Biodegradation pathways of contaminants such as benzene, toluene, ethylbenzene, xylene (BTEX), PAH and other aromatics require oxygen to initiate, or to keep going, the biodegradation process (Lu, et al., 2017), but often oxygen is a limiting factor, and when it is depleted, biodegradation changes from aerobic to anaerobic, and so also the microbial population and the rate of the reactions occurring. Anaerobic biodegradation is 1 to 2 orders of magnitude slower than the aerobic one (Kunucku, 2007), and oxygen application stimulates aerobic microorganisms' growth and their usage of contaminants as food and energy sources (Kunucku, 2007). There is often a need to supplement the microbial population with an electron donor, in order to keep aerobic conditions, and this is called 'enhanced in-situ bioremediation', while the addition of specific microbial population to the site is defined 'bioaugmentation'.

Oxygen releasing compounds (ORCs) have been used in order to provide soil, or groundwater, with sufficient oxygen. The most common ORCs used were hydrogen peroxide ($H_2O_2$) and magnesium peroxide ($MgO_2$) (Koenigsberg & Sandefur, 1999; Lu, et al., 2017), but hydrogen peroxide is usually readily consumed by metals and humic substance present in the soil, exhausting the oxygen source earlier than desired (Lu, et al., 2017). The ORCs in magnesium peroxide formulations is insoluble and release oxygen slowly when hydrated (Koenigsberg & Sandefur, 1999), and lately calcium peroxide (CP, $CaO_2$) has been commonly used for this purpose (Lu, et al., 2017). Common application methods are injection in the saturated zone or application using exchangeable filter socks (for groundwater remediation) or dispersion of powder in the soil (Kunucku, 2007; Lu, et al., 2017).

The main issues in the use of bioremediation are if and to what degree the contaminants can be degraded by the organisms already present in the site and to be able to guarantee aerobic conditions to the contaminated area, and the timeframe needed for the remediation (Kunucku, 2007). Moreover, in situ microbial degradation of PAH is often limited by their properties, among the others the low bioavailability and low water-solubility and other problems may be linked to the eventual creation of biofilms or to the clogging of the filters that provide the oxygen release compound (Badr, et al., 2004).

### *Soil flushing*

Soil flushing involves the extraction of the contaminants from the soil via a fluid injected into the contaminated area. The fluid is usually water or water combined with some additives that enhance contaminants desorption from the soil (Augustijn, et al., 1994), and depending on the type of contamination, various solutions can be used, such as water, complexing or chelating agents, reducing agents, acid or basic solutions, cosolvents and surfactants (USEPA, 1991). During the flushing, the contaminants are mobilized and can move together with the liquid to a collection system, needed in order to avoid that the contaminated mixture can move and reach unpolluted areas (USEPA, 1991). The mixture of liquid and contaminants is then pumped up to the surface, where the water is treated and the eventual additives partially recovered (Augustijn, et al., 1994), since the amount of solvent that can be recovered highly influences the cost of this remediation method. Soil flushing is effective in removing metals, soluble organic contaminants and some low soluble organic contaminants (depending on the type of additive used), such as PCBs, chlorinated benzenes, PAH, petroleum products, chlorinated and aromatic solvents (USEPA, 1991; USEPA, 2006). Soil flushing is used in combination with other techniques, since the liquid mixture of contaminants and water/additives has to be treated.

Limitations associated with this technique are linked to the type of soil, the availability of data regarding the characteristics of the aquifer below the contaminated area, the mixture of contaminants, bacteria fouling of infiltration and recovery systems and the time required for the technology to effectively treat the contamination (ranging from months, when using aggressive additives, to years) (USEPA, 1991). The technique does not perform good in soils with low permeability and/or high percentage of silt and clay-sized particles, soils with high content of organic matter and with pollutants that partition strongly to the soil and therefore desorb slowly (USEPA, 1991; Pagilla & Canter, 1999).

### *In-situ thermal treatment*

Thermal technologies have been used for contaminated soil remediation dating back to the 1980s, but with a deeper understanding on some of their properties gained only in recent years (Kingston, et al., 2014). The most common heating options used in thermal methods are three, and they are ‘steam-enhanced extraction (SEE)’, ‘thermal conductive heating (TCH, also known as ‘in-situ thermal desorption (ISTD)’) and electrical resistance heating (ERH) (Kingston, et al., 2014). Generally, these technologies aim to remove the contaminants increasing subsurface temperatures, consequently increasing vapour pressure to induce liquid-to-gas phase change, the partitioning to the gas phase or increasing the mobility of the contaminants reducing the viscosity and the interfacial tension, to facilitate liquid recovery (Kingston, et al., 2014).

Compared to technologies involving fluid injection, thermal treatments are faster and more uniform, evenly heating the entire volume of soil treated, and the drying and shrinking of the soil enhances the transport of the vaporized contaminants, due to a higher permeability (Stegemeier & Vinegar, 2000). Most of the contaminants are usually destroyed before reaching the surface, but the ones that are not are usually removed by air control systems with the steam vapour at the surface (Stegemeier & Vinegar, 2000).

Generally speaking, there are three levels of thermal treatment:

- Level 1 - Thermally Enhanced Free Product Recovery (TEFPR), where the subsurface is heated at temperatures between 70-100 $^{o}$C in order to enhance the pumping of the contaminants and make the remaining ones less mobile (Heron, et al., 2015). Only ISTD or ERH can be used for this technique.
- Level 2 – The contamination is treated at temperatures close to 100 $^{o}$C, depleting the more mobile and volatile compounds present in the contamination (more compounds respect to level 1) and reducing further the leaching capacity of the contamination left to. This method is referred to as In-Situ Thermal Solidification (ISTS). All the three heating methods described above can be utilized to heat the subsurface.
- Level 3 – The temperatures of the treatment are above the boiling point of water, with temperatures up to 200-300 $^{o}$C (Heron, et al., 2015). Only ISTD can heat the soil up to these temperatures (Heron, et al., 2015).

There are not geological constraints to the use of SEE, but some differences are present depending on the site conditions: typically, between 1 and 3 pore volumes of steam are injected in the soil, but for creosote and heavy soils it may be needed to inject up to 20 pore volumes if the remedial goals are stringent (Kingston, et al., 2014). Also, if the groundwater flow in the treatment zone cannot be controlled, a steam barrier against the influx of groundwater can be created by steam injection wells up gradient the treatment zone (Kingston, et al., 2014).

In the case of TCH/ISTD, there are different ways to heat the soil: through the use of areal surface blankets or from vertical or horizontal wells. The latter is a better option to reach greater depths. The physics of the processes consists in applying heat to the soil through a high-temperature surface in contact with the soil and then to transfer the heat through thermal conduction, which accounts for over 80% of the heat transfer (Stegemeier & Vinegar, 2000). However, this technique is sensitive to groundwater flow, due to its associated cooling in high-permeability zones that can slow the heating process or even prevent to reach the desired temperatures (Johnson, et al., 2009).

The limit of ERH is that it can raise the temperature of the subsurface no more than to the boiling point of water (100°C, 1 atm pressure). This technology is limited as well by the cooling influence of eventual groundwater flow (Kingston, et al., 2014).

*Stabilization/solidification*

Stabilization/solidification (S/S) technologies aim to immobilize contaminants mixing binding reagent(s) with the contaminated media (contaminated soil or waste) (Wilk, 2004; Leonard & Stegemann, 2010). Stabilization involves chemical changes that convert the contaminant into a less soluble, toxic or mobile form (Wilk, 2004; Leonard & Stegemann, 2010), while solidification refers to changes in the physical properties of the contaminant, involving the creation of a solid matrix to encapsulate (Wilk, 2004; Leonard & Stegemann, 2010). S/S is a widely used technique in disposal and management of contaminated media and it is considered an established treatment technology in contaminated sites remediation, waste management and brownfields restoration (Wilk, 2004). Common binding reagents are Portland cement, cement kiln dust (CKD), lime, lime kiln dust (LKD), lime and cement, limestone, fly ash, slag, gypsum, phosphate mixtures and industrial by-products binders (Wilk, 2004; Leonard & Stegemann, 2010). Depending on the binders used, energy requirements, fate of the mixture and target contaminants may differ. Energy requirements are low if industrial by-products are used, S/S has been reported effective on inorganic contaminants, while the effects on organics are being still discussed, and depending on the characteristics of the final product, it may be used as construction material (Leonard & Stegemann, 2010).

S/S has been frequently used in the treatment of inorganic contaminants, especially heavy metals, where it has been used to reduce the leaching potential of the contaminants from waste or large volumes of contaminated soil, sludge or sediments (Wilk, 2004). Treatment of organic contaminants has been carried out mostly with the use of cement, relying on cement ability to solidify the waste (Wilk, 2004), even though the effectiveness in treating waste with high levels of organic compounds is still debated, due to the detrimental effects that organic compounds may have on the binders (Leonard & Stegemann, 2010). In the last years, contaminants have been treated with S/S coupled with ISCO, where persulfate has been observed to be activated better and faster with ISS amendments than with other activating agents (Cassidy, et al., 2015).

### 2.6.3. Negative environmental impacts of the remediation techniques

Different stages of the remedial action can contribute to negative environmental impacts, such as the production and transport of the chemicals used, the energy requirements of the remedial action, the production and transport of the tools and machineries needed but also the undesired negative effects on flora, fauna, ecosystems and humans of chemicals mishandling, unwanted spills, leaching of chemicals in non-contaminated areas, both in the soil and in the groundwater. For the techniques described above, the stages contributing the most to negative environmental impacts have been identified.

Environmental performance of alternatives involving excavation and landfilling of the contaminated soil is evaluated taking into account the different impacts caused during excavation, removal of the contaminated soil, transport of the soil to the receiving facility and transport of clean filling soil to the site (Diamond, et al., 1999). Transport of the contaminants from the site to the landfill(s) and transport of the pristine soil to the site are the main contributors to the environmental impacts, and are caused by the need of fossil fuels and the emissions from the means of transport (Diamond, et al., 1999; Blanc, et al., 2004). The need of a sheet pile wall during the excavation might contribute to the secondary environmental impacts, due to the metal emissions during the production and use of steel (Lemming, et al., 2010). However, models still show poor or no agreement when characterizing metal toxicity (Lemming, et al., 2010), therefore it has to be evaluated case by case if taking into account impacts linked to sheet piling or not.

Environmental performance of in-situ techniques is evaluated taking into account different environmental impacts: environmental performance during the production of the chemicals, impacts due to transport of the chemicals from the producer to the site, impacts during the site remediation and the impacts on the environment when the site remediation is finished (handling of waste, contamination due to the chemicals, formation of by-products etc.). For the in-situ technologies, the common impacts are mainly due to fossil fuels need for the machineries, energy and electricity need and to the production and transport of the chemicals (Cadotte, et al., 2007). It can be assumed that materials for the boreholes and wells, as much as the machineries used for pumping the chemicals, would be the same for ISCO and bioremediation. Therefore, the amount of chemicals needed and their transport, together with the risk of leaching and chemicals toxicity would be the main drivers of the differences in the impacts between the different methods comprising injection of chemicals (Cadotte, et al., 2007), while the energy requirements would be the main driver of the thermal treatment impacts (Lemming, et al., 2010). Then, depending on the technique used and/or on the chemical injected in the subsurface, different environmental impacts can be due to ecotoxicity of the chemical, formation of dangerous by-products and eventual spreading of the contamination.

Regarding ISCO, large negative impacts are due to the production and transport of the needed chemicals to the site (Cadotte, et al., 2007). Therefore, the amount of oxidant needed and the distance from the site and the production plant would highly influence the impacts of this technique, while the impacts related to the materials needed (pumps, containers, wells, machineries), use of fossil fuels and electricity on-site have, in proportion, a lower share on the impacts, also due to the high reuse rate of most of the materials (Lemming, et al., 2012). The chemicals tested for ISCO are hydrogen peroxide and sodium persulfate, therefore their toxicity on humans and ecosystem, and the risk of unwanted chemical spreading of the technique has been investigated.

In-situ bioremediation implies activities that have environmental impacts, such as drilling of wells to inject or extract chemicals and contaminants, and eventual wells to extract or control contaminated groundwater (Diamond, et al., 1999). The time needed for the bioremediation to be effective can influence which step of the remediation has the main impacts, but production and transport of chemicals can be seen as the main cause of environmental impacts.

The main negative environmental impacts related to in-situ soil flushing can be assessed to be the same as the other in-situ technologies, with the addition of the impacts related to the implementation and of the structure to treat the contaminated water extracted downstream the contamination. The latter might be the cause of important impacts, but if a WWTP is already present on-site to treat the water from the works, the impacts due to this activity can be considered negligible. Hence, it can be assumed that the main environmental impacts are the ones due to the production and transport of the chemicals.

The use of solidification/stabilization has negative environmental impacts as well. The production and transport of the chemicals used for stabilization/solidification are the main cause of impacts related to the use of this technique.

In the case of in-situ thermal desorption, the main environmental impacts are due to on-site energy consumption for soil heating, that also causes depletion of energy resources (Lemming, et al., 2010). Some environmental impacts are also linked to the use of machineries on-site, but their share on the total impacts is low (Lemming, et al., 2010) and gets smaller with the increase in site size (Lemming, et al., 2013).

# 3. Methods

The work started with a literature review of contaminated sites management and sustainable remediation, and describing the case study and relevant remediation techniques (Sections 3.1 and 3.2). In order to carry out the sustainability assessment, the SCORE method and tool was used (Section 3.3), but expanded to be able to handle secondary impacts of the in-situ remediation alternatives (Section 3.4).

The methodology used to assess the sustainability of the different remediation techniques and to evaluate the results is based on the SCORE method (Rosén, et al., 2015), described later in Section 3.3. This framework was further developed to assess the environmental sustainability of in-situ techniques, as described in Section 3.4.

## 3.1. Literature review

The first part of the methodology consisted of a literature review about the state of the art on the management of contaminated sites, the concept of sustainable remediation and the techniques used in remediation projects. The theory of some common tools used for this purpose, such as multi-criteria analysis, cost-benefit analysis and life-cycle assessment was also investigated. Afterwards, a literature review about the most common ex-situ and in-situ technologies was carried out, with particular focus on the techniques that were studied for the site. This part was presented in Section 2.

## 3.2. Case-study Kolkajen-Ropsten

The work carried out in this project was based on a real case-study, where a remediation project was being designed and some different alternatives were being studied. Therefore, the case-study description was the second step of the methodology. The real site was described and the risk assessment that was performed on the site was presented, as well as the contaminants found on the site, their concentration, the clean-up goals and the techniques studied to be implemented. To simplify the analysis, the sustainability assessment carried out in this project was based on a conceptualization of the site as a result of a lack of precise data and due to a large heterogeneity of the site (see Section 5).

## 3.3. The SCORE method

The sustainability assessment was carried out using the SCORE method and was expanded to assess the environmental sustainability of in-situ techniques, described in Section 3.4. The information on the SCORE method presented in this section is taken from Rosén et al., 2015, where it is presented and described.

The SCORE method, developed by Rosén, et al, (2015), is based on the theory of MCDA, using a linear additive function, but it is developed specifically for remediation projects, trying to handle all the difficulties associated to the usual MCA/MCDA. Here, sustainability is assessed by evaluating the performance of the remediation options with regard to three different sustainability domains: social, environmental and economic. Moreover, each alternative for a remediation project is evaluated relative to a reference alternative, usually the no action alternative, using a set of criteria to assess the different effects for each domain. In this way, SCORE is able to identify which alternative is the most sustainable/least unsustainable, helping to move towards sustainable development. However, it has to be point out that the ‘winning’ alternative is the best one only relatively to the ones analysed: there might be better options, but not included in the assessment. In the SCORE method, moreover, all the three sustainability domains are equally important: the dominating model is a Venn diagram of overlapping circles and where the three circles overlap there are the sustainable solutions, as shown in Figure 1 from Rosén et al., 2015.

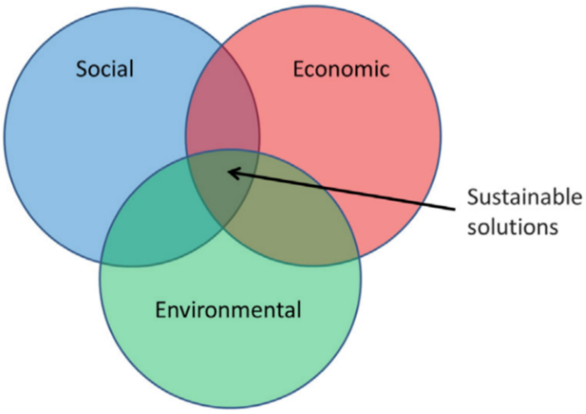


*Figure 1. Venn diagram of the three different sustainability domains.*

SCORE also allows to give different importance to the three domains, by giving them different weights in the overall sustainability assessment of the remediation alternatives.

### 3.3.1. The SCORE framework

The SCORE framework is shown in Figure 2.

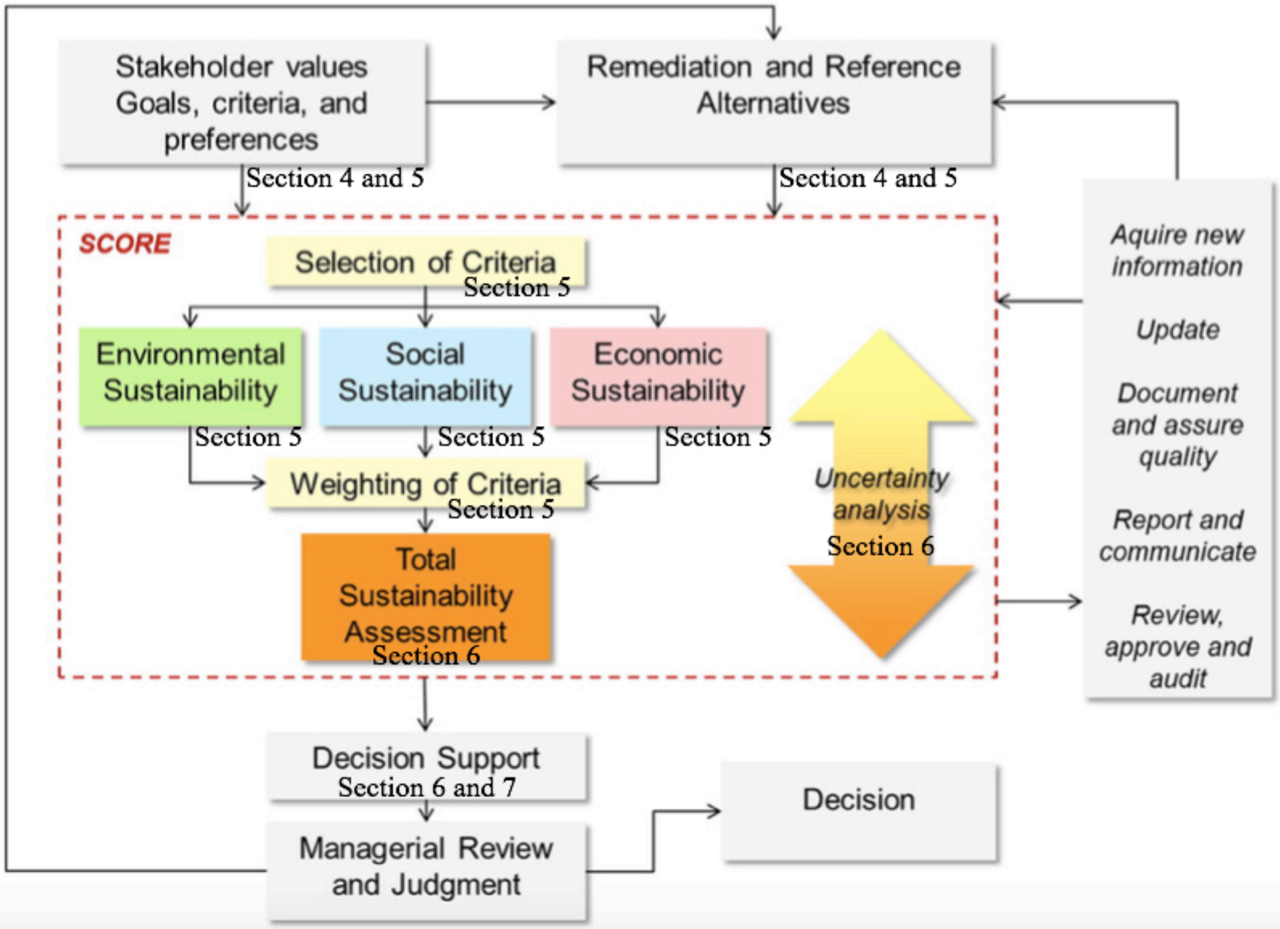


*Figure 2. The SCORE framework, from Rosén et al., 2015, used to perform the sustainability assessment presented in this work. It is shown in which part of the project each part is further described or developed.*

The scoring in the environmental and social domains together with the quantification of monetary costs and benefits in the economic domain help to calculate the expected effects of the different remediation alternatives. In order to do so, a normalized total score is calculated for each alternative, depending on the different importance given to the different criteria, and using a linear additive approach, keeping in mind that scoring and quantifications resulting from the analysis are associated with uncertainties. A non-compensatory approach is used in order to distinguish between alternatives that might lead towards weak or strong sustainability: the concept of weak sustainability entails that the negative impacts in one domain can be compensated by positive performance in another, while strong sustainability does not allow this compensation.

Using this model, it is important to define the boundaries specific to the assessments, in order to decide and describe which part of the remediation project is going to be included in the calculations. How in deep in the impacts pathway it is necessary to go has to be defined by a boundary, the temporal boundary is necessary in order to delineate the time perspective used and the spatial boundary has to be defined to delimit the assessment to certain areas. However, the system boundary of SCORE limits this model to be used with a given land-use scenario.

The SCORE method was developed using the cause-effect chain concept, where the cause is the remediation itself, the effects are associated with the remediation and with the change in the source contamination and can be positive or negative, taking place at different locations (on-site and off-site). These effects act on different receptors (humans, ecosystems and natural resources) and can be long or short-term.

### 3.3.2. Performance criteria

The key performance criteria in SCORE are related to the three domains: environmental, social and economic. The criteria in the environmental and social domains have sub-criteria representing on-site and off-site effects, likewise the effects resulting from changes in source contamination or due to the remedial action. Table 1 shows the key criteria for the different domains, and in the next sections they are explained further. It is important to point out that the inevitable effects and links between the different domains do not have to be confused and addressed as double-counting.

*Table 1. Performance criteria for the different domains.*

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

*Environmental criteria*
The key criteria identified for the environmental criteria in SCORE are listed in Table 2.

*Table 2. List of the key criteria for the environmental domain and their description, readapted from Rosén et al., (2015).*

| Key Criteria | Description |
|---|---|
| E1 – Soil | The soil criterion comprises the ecotoxicological risks due to remedial action and/or source contamination on the soil ecosystem and the effects on the soil function of the remedial action and/or source contamination |
| E2 – Flora and fauna | Physical impacts on flora and fauna from the remedial action |
| E3 – Groundwater | Effects in ecotoxicological risks and/or groundwater quality potentially affected by the source contamination and/or the remedial action |
| E4 – Surface water | Effects in ecotoxicological risks and/or surface water quality potentially affected by the source contamination and/or the remedial action |
| E5 – Sediments | Effects in ecotoxicological risks for organisms in the sediments potentially affected by the source contamination and/or the remedial action |
| E6 – Air | Total emissions to air caused by the remedial action |
| E7 – Non-renewable natural resources | The amount of non-renewable natural resources used by the remedial action |
| E8 – Non-recyclable waste | The amount of non-recyclable waste produced by the remedial action |

All the criteria listed above have sub criteria designed to specify if the effects are on-site or off-site and due to the remedial action (RA) or the source contamination (SC). Some assumptions were needed when defining the different risks and impacts on the environmental matrixes from the contamination and the remedial action itself: (1) soil functions were assumed to be affected only by the remedial action, (2) ecotoxicological risks in soil were assumed to be influenced by change in source contamination and remedial action, and that (3) soil functions and ecotoxicological risks off-site were not influenced by the remediation, (4) remedial action and change in source contamination were assumed to influence groundwater, surface water and sediments on-site and off-site, while (5) only the remediation action was assumed to have effects on air, non-renewable natural resources and non-recyclable waste. The scoring of the environmental criteria is usually based on existing information from analyses and reports, and it is important to stress that there are no restrictions on adding sub-criteria, if it is necessary for evaluating separate effects on-site or off-site for certain criteria.

In this project, the cost of each of the 5 alternatives evaluated was estimated according to literature and project-specific data, and some benefits were estimated. However, due to data limitations and time constraints, it was not possible to estimate some important externalities and benefits, therefore a qualitative CBA was also carried out. Section 5.6 provides all the details necessary to understand how this methodology was applied to this project.

*Social criteria*
Social criteria identified in SCORE are listed in Table 3.

*Table 3. List of the key criteria for the social domain and their description, readapted from Rosén et al., (2015).*

| Key Criteria | Description |
|---|---|
| S1- Local environmental quality (LEQ) and amenity, including physical disturbances | Effects on e.g. recreational values, accessibility of the area or odour/noise in the area |
| S2 – Cultural heritage | Positive or negative effects on cultural heritage items. |
| S3 – Health and safety | Effects on human health and safety due to the presence and/or spreading of the contaminants |
| S4 – Equity | Effects on the vulnerable groups of the society |
| S5 – Local participation | Effects on local community |
| S6 – Local acceptance | Acceptance of the remedial alternative by the local community |

Social criteria are also divided into sub-criteria, in order to point out if the effects are due to the remedial action or to the change in source contamination. The land use change that a remedial action involves has an impact on the scoring of the social criteria, even if SCORE was not developed to support decision-making on land use planning. The social effects can be scored by experts and people with local knowledge, using existing information, while the criterion 'local acceptance' should instead reflect how the local population see the different remediation strategies, therefore consultation with the local community is necessary in order to score this criterion.

In this work, the social criteria were scored during an internal meeting, where the impossibility of having the stakeholders present was overcame by expert judgement and careful evaluation of the social implications of each remedial alternative studied, of the site, its surroundings and its features.

*Economic criteria*
In the economic domain, the key criterion is social profitability, which is assessed and evaluated using cost-benefit analysis (CBA). Therefore, all the impacts that are important for a CBA have to be included and defined in SCORE, and they can be benefits ($B$) or costs ($C$). The benefits are: (B1) increased property value on-site, (B2) improved health, (B3) increased provision of ecosystem services and (B4) others that could be relevant depending on the case. The costs are: (C1) remediation costs, (C2) impaired health due to remedial action, (C3) decreased provision of ecosystem services due to remedial action and (C4) other negative externalities that could be relevant depending on the case. Then, the net present value (NPV) during the time span of the remediation process is used to calculate the social profitability in monetary terms.

In order to provide for a fair distribution of benefits and costs among the different actors, for each cost and benefit item it is assigned who is the main beneficiary or payer (e.g.: developer, public, employees). This distributional analysis is used to study the NPV for the different stakeholders.
Equation 4 shows how the NPV is calculated:

$$NPV_i = \sum_{t=0}^{T} \frac{1}{(1+r_t)^T} (B_{i,t} - C_{i,t}) \qquad \text{Eq. 4}$$

Where $B_t$=$B1_t$+$B2_t$+$B3_t$+$B4_t$ and $C_t$=$C1_t$+$C2_t$+$C3_t$+$C4_t$ (sum of costs and benefits at time t), $r_t$ is the social discount rate at t and T is the time horizon. The alternative (*i*) with the highest NPV is the most profitable one. However, it is seldom possible to monetize entirely all the costs and benefits, therefore a qualitative discussion concerning the non-monetized items should be provided. There is no time boundary for the NPV calculation, the time horizon for the calculation is decided depending on the project and on the cost and benefits considered. The evaluation team decides which discount rate to use, according to international and country-specific guidelines.

### 3.3.3. Weighting and scoring of the criteria

Although the starting point of a SCORE analysis is that all key criteria are equally important, for each domain *D*, the different key criteria does not necessarily have the same importance, here quantified with a numerical weight. For each criterion (*k*) and sub-criterion (*j*) the importance *I* can be assigned between somewhat important = 1, important = 2 and very important = 3, while the criteria not used in the scoring are left out already at the beginning of the assessment, and here the value of not important = 0 is assigned. The weight of the key criterion is then shown in equation 5:

$$W_{k,D} = \frac{I_{k,D}}{\sum_{k=1}^{K} I_{k,D}} \qquad \text{Eq. 5}$$

While the weight of each sub-criterion is shown in equation 6:

$$W_{j,k} = \frac{I_{j,k}}{\sum_{j=1}^{J} I_{j,k}} \qquad \text{Eq. 6}$$

The weights of criteria and sub-criteria have a value between 0 and 1, and the sum of all the criteria is equal to 1 and the sustainability index H is calculated for each domain for every remediation alternative, as the weighted sum of the scorings, using a linear additive approach, as shown in equation 7:

$$H_{D,j} = \sum_{k=1}^{K} w_{k,D} \sum_{j=1}^{J} w_{j,k,D} Z_{j,k,D} \qquad \text{Eq. 7}$$

Equations 5, 6 and 7 are used to weight the criteria and sub-criteria in the environmental and social domains, while in the economic domain, the NPV calculation is based on monetary measures, thus no weighting is done. Finally, for each alternative (*i*), a normalized sustainability score is calculated according to equation 8:

$$\begin{aligned} H_i = 100[&W_E \frac{H_{E,i}}{Max\left[Max\left(H_{E,1..N}\right); \left|Min\left(H_{H,1..N}\right)\right|\right]} \\ &+ W_{SC} \frac{H_{S,i}}{Max\left[Max\left(H_{S,1..N}\right); \left|Min\left(H_{S,1..N}\right)\right|\right]} \\ &+ W_{NPV} \frac{NPV_i}{Max\left[Max\left(NPV_{1..N}\right); \left|Min\left(NPV_{1..N}\right)\right|\right]}] \end{aligned} \qquad \text{Eq. 8}$$

In the equation, $H_E$ is the score of the environmental domain, $H_S$ of the social domain, NPV is the net present value and W is the weight of each domain. The result has a value between -100 and +100, and a normalized score greater than zero means that the alternative leads towards sustainability to a higher degree than the reference alternative. However, due to the site-specific characteristics of the values used, it has to be kept in mind that the normalized score is a relative ranking of the analysed alternatives, therefore scorings from one site cannot be compared with scoring from other sites. Also, through a detailed analysis of the equation used to calculate the normalized score, it is possible to identify which criteria need to be improved, in order to improve any alternative to lead towards sustainability to a higher degree.

All the remedial alternatives that are evaluated in SCORE are assessed and compared against a reference alternative, chosen by the team that evaluates the alternatives and it is typically the no action alternative, in order to see what would change if nothing would be done to remediate the site. The remedial alternatives must be specified before starting with the SCORE evaluation, and they have to meet certain objectives regarding the remediation targets, time, budget, technical feasibility, legal aspects and acceptable risk levels. Obviously, the constraints are specific for each project, and are not pre-defined by SCORE. The reference alternative, instead, does not have to meet these above-mentioned constraints and it cannot include remediation.

The criteria that can be chosen are the ones listed in Table 1. It is not mandatory to include all of them, but in case any of them are excluded, the reason should be provided and carefully motivated.

The performance of each criteria in the environmental and social domains are scored using a semi-quantitative performance scale: Very positive effect: +6 to +10; Positive effect: +1 to +5; No effect: 0; Negative effect: −1 to −5; Very negative effect: −6 to −10, and in order to keep the results transparent, each scoring has to be motivated.

For the CBA, relevant costs and benefits can be chosen from the ones listed in Appendix VII, and among these, the items that is not possible to monetize but are believed to be relevant are considered somewhat important or very important in order to be able to give them a qualitative assessment and use them in the results of the CBA.

### 3.3.4. Uncertainty analysis in SCORE

Generally speaking, uncertainties that can influence mathematical models and experimental measurements can be of various origin, depending on parameters used, structure of the model used, numerical errors/approximations, variability of experimental measurements and interpolation. Also, uncertainties can be aleatoric, i.e. statistical uncertainties representative of unknowns that differ every time an experiment is run (due to lack-of-knowledge), or epistemic, i.e. systematic uncertainty due to inaccuracies of measurements or effects neglected by the model (due to natural variability) (Söderqvist, et al., 2015). Different kinds of uncertainties can be represented using statistical distributions, and Table 4 shows the most common ones.

*Table 4. Most common statistical distribution and their use, adapted from Burgman, (2005).*

| Type of distribution | Parameters for which is used |
|---|---|
| Constant | With a well-known/fixed value |
| Uniform | Few data available, but firm bounds are known |
| Normal | Variable made up of the sum of independent random variables |
| Lognormal | Variable made up of the product of a set of independent random variables |
| Triangular | Little is known, but upper and lower bounds and most likely value have been estimated |
| Beta | Qualitative information is available and upper and lower bounds and most likely value have been estimated |

Uncertainty analysis was implemented in SCORE because it is important to study the sensitivity of a model to evaluate the magnitude of uncertainty and to assess dependencies among parameters. A common way to do that is to use a Monte Carlo simulation approach (Burgman, 2005): the main idea of Monte Carlo analysis is that it is necessary to build a model for the uncertainties of the parameters of a model that are uncertain, and this can be done running the model under analysis over and over (Burgman, 2005). This method helps to perform risk analysis exploring the changes in model's outputs varying the factors that are uncertain, substituting the value of these parameters from a range of values taken from a probability distribution (Burgman, 2005). Each simulation consists of repeating random samples from the input probability distribution and performing statistical analysis, and the result is a probability distribution of the different outcomes.

Since the effects of remedial activities can never be measured exactly, their scores and quantifications have some degrees of uncertainty, due to both lack of knowledge and natural variability. A Monte Carlo simulation approach is used in SCORE to treat uncertainties related to scores and cost-benefit items. Uncertainties in scores are assigned in three steps: first, the possible range of scorings for the specific sub-criterion is selected (-10 to +10 if the entire scoring range is possible, 0 to +10 if no negative effects are possible and -10 to 0 if not positive effects are possible), the most likely score according to the scale shown above is then estimated and finally the uncertainty category level is assigned between 'low', 'medium' and 'high'. The result of this three-step procedure is a scaled beta probability distribution that represents the uncertainty related to the scoring. The standard deviation values that represent the uncertainty categories were defined by the team that developed SCORE, and they are shown in Table 5.

*Table 5. Uncertainty representations of scorings.*

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

In SCORE, the size of the uncertainty interval representing high uncertainty should ideally be double the size of the interval representing low uncertainty, while medium interval should be in between, as shown in an example of beta distributions with high and low uncertainties for the same score (+2 in this case) in Figure 3. Uncertainty distribution for costs and benefits is implemented in two steps: (1) providing the most likely value (MLV) of the present value (PV) of each of the cost and benefit items, and (2) assessing the uncertainty level of the estimation of the MLV assigning a value between high, medium and low. The result of this procedure is a log-normal distribution representing the uncertainty of the cost or benefit item, as shown in Figure 3. These three standard levels of uncertainties were decided to correspond to the error factors 3.16, 2 and 15 respectively by the team that developed SCORE method (Rosén et al., 2015). Also, credibility (or certainty) of the interval between the lower credibility level (LCL) and the upper credibility level (UCL) was set to 90%.

The uncertainty analysis is already built-in in the SCORE model and Oracle Crystal Ball is the program used for this purpose, a spreadsheet-based tool for predictive modelling, forecasting, simulation, and optimization that performs Monte Carlo simulations (Oracle, 2018). Section 6 and 7 present the results and discussion of the uncertainty analysis.

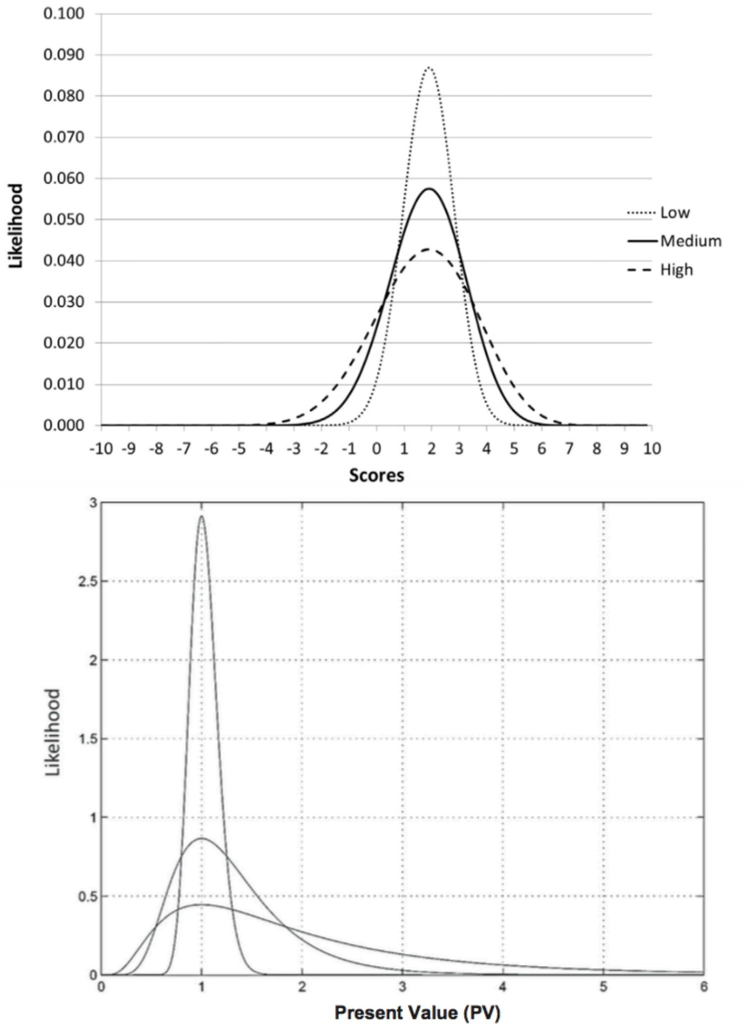


*Figure 3. Different beta distributions of uncertainties for a most likely score of +2 (top figure), and log-normal uncertainty distributions for the three levels of uncertainty for a PV=1 (bottom figure). Figure from Rosén, et al., 2015.*

## 3.4. Environmental criteria scoring: implementation of in-situ techniques assessment in SCORE

The SCORE framework was expanded to assess the environmental sustainability of in-situ techniques, as shown in Figure 4.

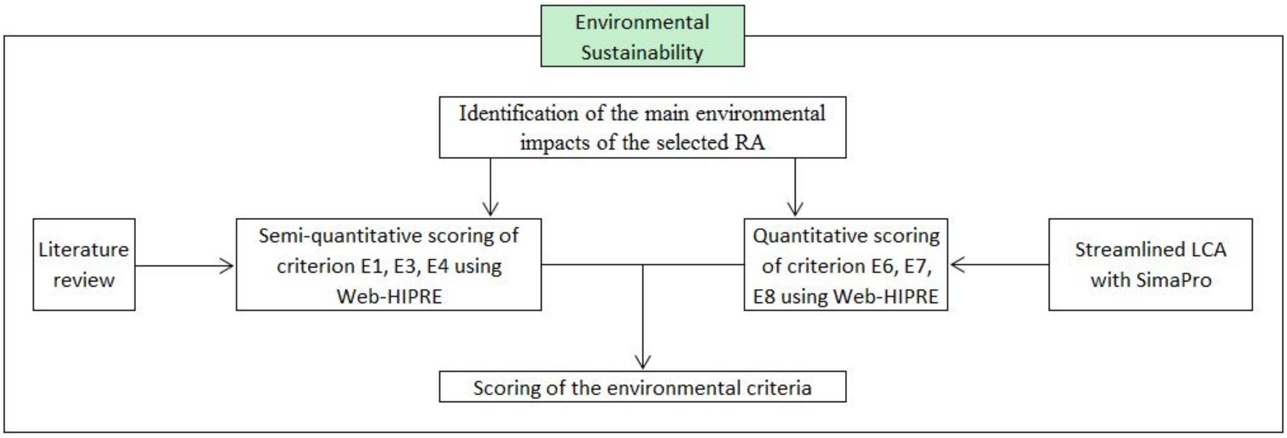


*Figure 4. Methodology that was used to implement the assessment of the environmental sustainability domain for in-situ techniques in SCORE.*

The assessment of in-situ techniques in SCORE was done on two levels: (1) in a semi-quantitative way for the secondary impacts of the remedial action on soil, groundwater and surface water (criteria E1, E3 and E4), and (2) in a quantitative way performing a LCA and using the results to score air and natural resources criteria (criterion E6 and E7) and in a quantitative way for the waste generation (criterion E8), assessing the amount of waste produced by each RA. The next sections describe these two different approaches, while Section 5 presents the application of this methods in SCORE for the case-study.

### 3.4.1. Semi-quantitative scoring of the secondary impacts of the remedial actions

This approach was used to score the criteria regarding soil (E1), groundwater (E3) and surface water (E4), where the subcriteria 'Ecotox risk RA on-site', 'Grondwater RA on-site' and 'Surface water RA off-site' were further divided in three sub-subcriteria each. These sub-subcriteria take into account the risk of spreading the contamination, of by-products formation and of having other negative environmental impacts for each remediation alternative. These new sub-subcriteria were then scored semi-quantitatively according to information found in literature and case-studies, assigning values between 0 and 6, where a score of 0 corresponds to 'null' effect or risk, a score of 1-2 to 'low' effect or risk, a score of 3-4 to 'medium' effect or risk, a score of 5-6 to 'high' effect or risk.

The assigned values were used as inputs in Web-HIPRE, a MCDA online tool (described further later), in order to score the above-mentioned subcriteria of E1, E3 and E4 in regard to the five different alternatives. Web-HIPRE gives the scores with a scale between 0 and 1 for each alternative, scale that was then transformed in the same scale used in SCORE (from -10 to +10), in order to use the values as inputs in the SCORE assessment.

### 3.4.2. Quantitative scoring of E6, E7 and E8

The air emissions (E6) were quantified by means of a streamlined LCA, dividing the air criterion in the four new subcriteria 'Global warming', 'Ozone formation', 'Terrestrial acidification' and 'Fine particulate matter formation' that were selected from the outputs of the LCA. These outputs were normalized dividing them by the output values of a worst-case scenario.

Initially, the worst-case scenario should have been the complete excavation of the site and the consequent landfilling of all the soil, but it was noticed that some of the alternatives had higher impacts than this worst-case scenario, therefore the normalization was carried out dividing the results of each category by the highest value of the five alternatives. It was therefore possible to obtain values between 0 and 1 for the three sub-subcriteria, and use them as inputs in Web-HIPRE, applying then the same methodology described in the previous section to obtain input values for SCORE.

The effects on non-renewable natural resources (E7) were quantified by means of a streamlined LCA, and quantifying the amount of pristine soil needed by each alternative, dividing then the criterion in the three new sub-criteria 'Pristine soil', 'Fossil resource scarcity' and 'Water consumption'.
The first sub-criterion was scored quantifying the amount of pristine soil needed for each remediation alternative and normalizing it dividing the values by the ones of a worst-case scenario (all the soil at the site excavated and replaced). The other sub-criteria were scored as for E6, for the same reasons. The normalization gave values between 0 and 1, that were used as inputs in Web-HIPRE, in the same way as described above for E6. The passages to obtain the inputs values to use in SCORE were the same as for criterion E6.

### 3.4.3. Streamlined life-cycle assessment

LCA was applied in this project to make a better assessment of the effects of some of the environmental criteria.

However, it is important to point out that a classic LCA was not used, instead a streamlined LCA approach was used. Often it can be very complex and time consuming to carry out a life-cycle assessment, and streamlined LCA is a practice that has been widely adopted to make it more manageable (Todd & Curran, 1999). There are different ways to perform a streamlined LCA, such as limiting the scope, use qualitative information, use surrogate processes, remove of upstream or downstream components, use only specific impact categories or select the most significant input factors (Hunt et al., 1997; Todd & Curran, 1999; European Commission, 2008). These ways to streamline LCA can be used alone or coupled together (European Commission, 2008), depending on the aim of the study.

The functional unit, which describes the service analysed and compared in the LCA, was defined in this study to be the treatment of the whole contaminated site, which should lead to a removal of the contaminants to reach the remediation goal. Thus, the different remedial actions can be compared if they provide the same function (Blanc, et al., 2004). For the present LCA study, system boundaries included the stages of the remediation systems that were identified as the main drivers of environmental impacts (based on literature findings). Simplifications common to other LCA studies are present in this analysis, such as exclusion from the analysis of hardware manufacturing and activities of minor role (such as lab analyses) (Lemming, et al., 2010). However, in the light of the streamlined LCA approach also the aspects that were assessed to have low contribution to the impacts (based on literature studies) or that could have been considered common for the different techniques were disregarded, such as site preparation (setting-up of the technical installations, production and transport of needed equipment) and transportation of workers on-site, as further described later on in Section 5.4.

The attributional perspective was used in this LCA because it aims to "quantify the environmental impacts that can be attributed to the product system based on a mapping of the emission and resource flows that accompany the product as it moves through its life cycle, applying representative average data for all processes involved in the life cycle in a book keeping approach" (Bjørn, et al., 2018b). It differs from the consequential approach, that takes into account how the broader economic system is affected by the results of the LCA (Bjørn, et al., 2018b). The attributional LCI modelling aims to answer the question "What environmental impacts can be attributed to product X?", that seemed more relevant for the scope of this study than the question at which the consequential LCI modelling aims to answer: "What are the environmental consequences of consuming X?" (Bjørn, et al., 2018c). Moreover, the attributional perspective was chosen because, according to ILCD recommendations on LCI modelling choices, the decision context in which this study was carried out was for a Situation A (i.e. that concerns micro-level decision support) (EC-JRC, 2010).

EcoInvent 3.0 was used to look for data, because this database is widely used worldwide and the LCA community agrees on the accuracy of the information it contains (Wernet, et al., 2016). Since information for many chemicals were not found, the databases used to look for information were extended to Agri-footprint, ELCD (European Life Cycle Database), Industry data 2.0 and USLCI (U.S. Life Cycle Inventory Database). The life-cycle impact assessment (LCIA) method used was ReCiPe 2016 Midpoint, Hierarchist version. This is the default ReCiPe midpoint method, and it provides state-of-the-art method to convert to a limited number of impact scores the life cycle inventories, both on midpoint and endpoint level (Huijbregts, et al., 2017).

*SimaPro LCA software*

To perform the above-mentioned streamlined LCA, the SimaPro software was used. It is a software developed by PRé Sustainability used to collect, analyse and monitor the sustainability performance of different products and service through a transparent LCA process, measuring their environmental impacts (PRé Consultants B.V., 2018a). The goal and the scope of the LCA can be defined in specific sections, where it can also be decided which libraries to use: libraries are life cycle inventory databases and SimaPro currently includes ecoinvent v3, Agri-footprint, USLCI, ELCD, EU and Danish Input Output, Industry data v.2 and Swiss Input Output (PRé Consultants B.V., 2018b). After that, it is possible to choose from the databases the products to insert in the analysis, or to create new products, mixing existent products and processes. Here, it is important to clearly define the inputs and the outputs of the process. It is possible to define inputs and outputs of production, transport and/or transformation of natural resources and of materials and processes from the 'technosphere', i.e. the human-made technologies. When the processes to analyse are clearly defined and comprise all the relevant information, it is possible to analyse the results: a network tree shows the main 12 processes included in the creation of the final product and their impacts, and tables and graphs show the total impacts, scored from different perspectives, such as climate change potential, toxicity, use of natural resources and others.

### 3.4.4. Web-HIPRE MCDA software

As shown in Figure 2 Web-HIPRE (HIerarchical PREference analysis on the World Wide Web) was implemented to score the sub-criteria already present in the SCORE framework, adding new 'sub-subcriteria', scored using the results from literature review on the assessed techniques and results from the streamlined LCA. Web-HIPRE is an online tool for decision analytic problem structuring, multicriteria evaluation and prioritization developed by Aalto University (Mustajoki & Hämäläinen, 2000). It provides an implementation of multi-attribute value theory (MAVT) using an additive value function, structuring the decision problem visually in a decision tree, where it is possible to define overall objective, criteria and possibly subcriteria and define attributes ranges, the value function for attributes and the weight elicitation (Mustajoki & Hämäläinen, 2000). It is also possible to perform a sensitivity analysis of the results. Section 5.4 explains further how this tool was implemented to score the environmental criteria in SCORE.

# 4. Case study: Kolkajen-Ropsten site

The Kolkajen-Ropsten site is located in Norra Djurgårdsstaden, Stockholm, Sweden (Figure 5). In the past, the area has been the main industrial port for the city of Stockholm for many years. Moreover, due to the proximity of the Stockholm Gasworks, the three parts of the waterfront, Kolkajen, Tjärkajen and Ropsten, played a role in managing, storing and processing the mountains of coal that were arriving to the city.

Nowadays, the progress in the energy production field rendered the Gasworks obsolete and opened the opportunity to rearrange the use of this part of the city and today, Norra Djurgårdsstaden is one of the largest urban development areas in Northern Europe (ADEPT, 2017). It is predicted that over the next 20 years this development will house over 12 000 new homes and 35 000 new jobs, together with the creation of a new cultural area, the Stockholm Gasworks (ADEPT, 2017). However, the long-term and intensive industrial activities in the area has caused contamination of sediments, soil and groundwater. Therefore, in order to safeguard the ecosystem and to make redevelopment of this area possible, remediation of the contamination is necessary.

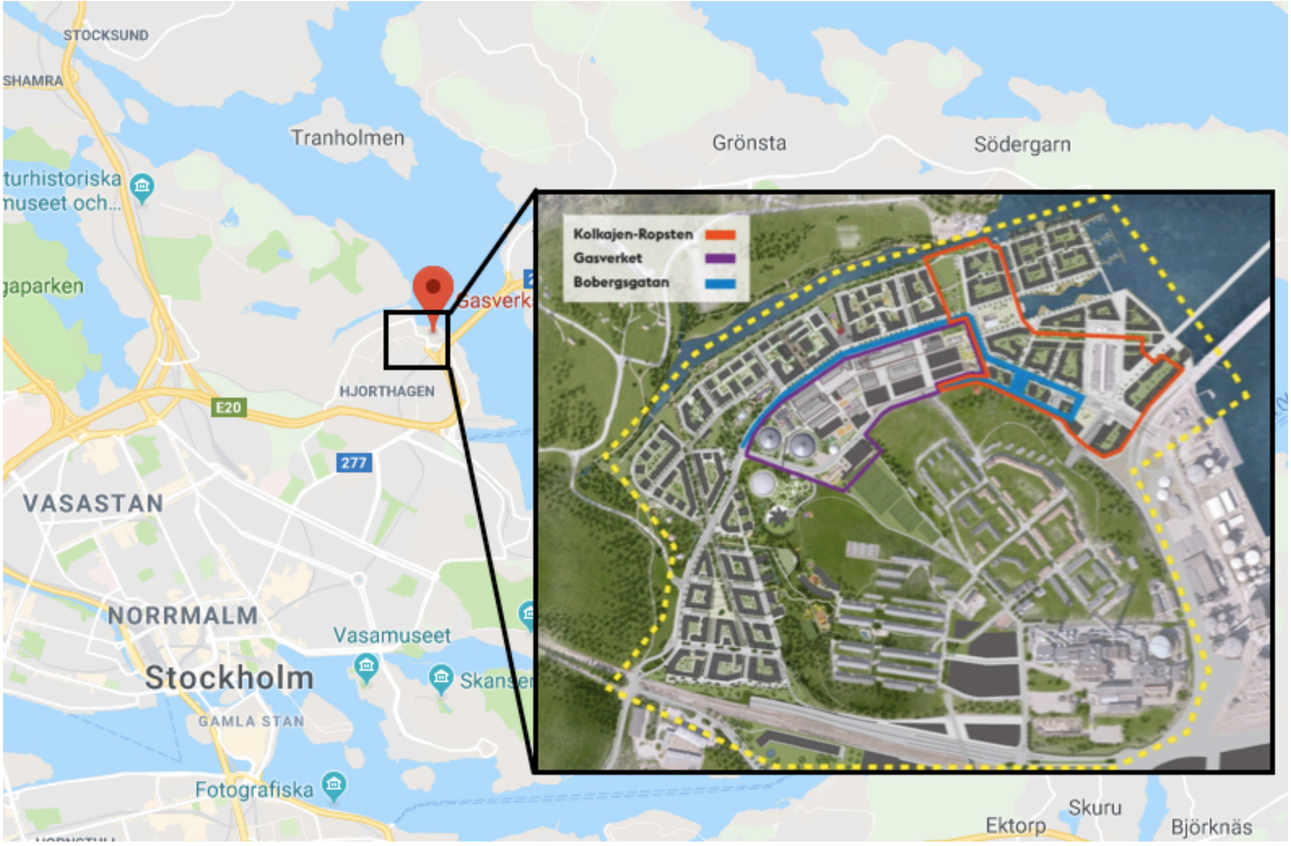


*Figure 5. The Kolkajen-Ropsten site. The map shows the location in the city of Stockholm. The squares zoom on the site.*

## 4.1. Contamination at the site

The risk assessment for the site was conducted by Kemakta Konsult AB in 2016 (Kemakta, 2016). The contamination at the site was investigated by means of sampling of soil, groundwater, pore air and sediment. Contamination of the different media were investigated by means of chemical analyses, leaching tests and screening analyses. The results showed that large parts of the area have been contaminated with polycyclic aromatic hydrocarbons (PAH), with concentrations over site-specific guideline values.

The risk assessment concluded that, where contaminant concentrations exceeded site-specific limit values, a long-term health risk for humans in the houses planned to be built on this site was present, due to soil contact and inhalation of vapours intruding the buildings. Figure 6 shows a sketch of the possible pathways of these contaminants and how they can migrate in the environment and affect humans.

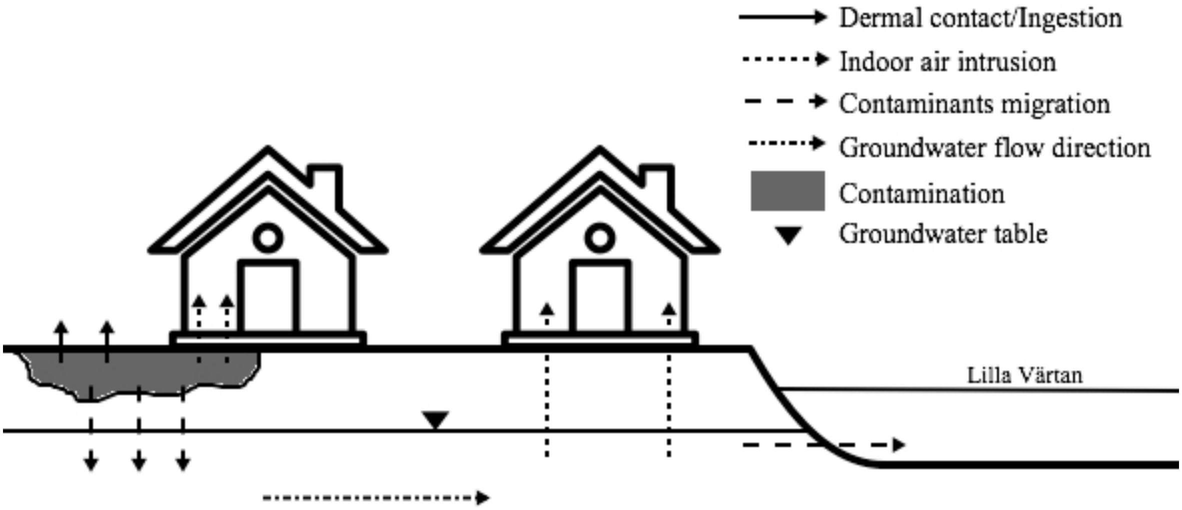


*Figure 6. Conceptual sketch on how humans can be exposed to contamination at the site, and how contaminants can migrate from the contaminated area. The information on how contaminants can migrate from the site is taken from Kemakta, 2016.*

#### 4.1.1. Soil contamination

The soil contamination in the area is predominantly comprised of tar by-products, above all PAH, but also benzene and petroleum hydrocarbons. In some places, arsenic and cyanide have been found in concentrations above site-specific guideline values. In certain areas, mainly around those places where tar was produced, extreme high concentrations of tar have been observed in soil as well as in groundwater.

Figure 7 shows PAH concentration in the soil at the site and Figure 8 shows the locations where the tar in free phase was found and where there was a strong smell of tar or oil. Table 6 shows the current pollution situation in the soil at the site, the guideline values and the target values to reach. Regarding the soil, only PAH are shown, since they are the main contaminants (Kemakta, 2016).

*Table 6. Values of the contaminants in the soil at the site and site-specific guideline values. Values shown are the maximum and minimum of the measured PAH-16 concentration in the soil, divided into light, medium and high PAH according to the proportion: PAH-16=25% PAH L, 51% PAH-M and 24% PAH H (Kemakta, 2016).*

| | **Current situation (mg/kg TS)** | | | **Integrated site-specific target values for Kolkajen-Ropsten (mg/kg TS)** | **Goals for Norra Djurgårdsstaden (mg/kg TS)** |
|---|---|---|---|---|---|
| | Max | Min | Mean | | |
| PAH-16 | 94 000 | 0.12 | 1 503 | - | - |
| PAH L | 23 500 | 0.03 | 376 | 170 | 170 |
| PAH M | 47 940 | 0.06 | 766 | 55 | 55 |
| PAH H | 22 560 | 0.03 | 361 | 30 | 30 |

### 4.1.2. Groundwater contamination

High levels of oil pollution and PAH have been found in groundwater, in areas where tar was also present in free phase. Noticeable levels of naphthalene and benzene have also been measured in the pore gas at hot spots at the old tar factory (a parking space today), the boat club and downstream Fortum, south of the site, where a benzene plant was located, at concentrations that can lead to elevated levels in indoor air, posing a health risk for the eventual future inhabitants. In the majority of the points investigated, contamination exceeded the guideline values for groundwater. The levels of benzene and other lighter aliphatic fractions, measured at the boat club and at the parking lot, indicated that the present concentration in groundwater could lead to elevated values registered also in indoor air in the new houses planned to be built, hence posing a health risk.

Moreover, contaminants can spread with groundwater to Lilla Värtan, the strait that separates mainland Stockholm and the municipality of Lidingö, and contaminate further the surface water and the sediments. Thus, the need to remediate contaminated groundwater was assessed to be high. However, important results on groundwater quality would be obtained already through the remediation of contaminated soil. Figure 9 and 10 show the highest concentrations of PAH and benzene measured in the different sampling points in groundwater. Table 7 shows the site-specific guideline values for groundwater for the risk of vapour infiltration in the new buildings that will be built and for spreading to surface water, and the target values to reach. Only the light PAH were measured because the heaviest aliphatic fraction (> C16-C35) has very low volatility and is considered not to present a risk for penetration with air in buildings (Kemakta, 2016).
Benzene was also tested and shown in groundwater because of its high carcinogenic potential in infiltrated air into buildings. The concentration shown as 'current situation' is the mean of the values measured on-site.

*Table 7. Concentration of contaminants in the groundwater, guideline values for avoiding risk of contaminants intrusion into the buildings and spreading to the groundwater, and site-specific target values to reach (Kemakta, 2016).*

| | **Current situation (µg/l)** | | | **Threshold concentration for penetration with air into building (µg/l)** | **Threshold concentration for spreading to surface water (µg/l)** | **Goal (µg/l)** |
|---|---|---|---|---|---|---|
| | Max | Min | Mean | | | |
| PAH L | 21 000 | 0.28 | 3 451 | 2000 | 300 | 300 |
| PAH M | - | | | 20 | 10 | 10 |
| PAH H | - | | | 600 | 1 | 1 |
| Benzene | 3 970 | 0.2 | 274 | 100 | 1000 | 100 |

The group PAH L includes naphthalene, acenaphthylene, acenaphthene, PAH M includes fluorene, phenanthrene, anthracene, fluoranthene, pyrene, PAH H includes benz[*a*]anthracene, chrysene, benzo[*b*]fluoranthene, benzo[*k*]fluoranthene, benzo[*a*]pyrene, dibenz[*a*,*h*]anthracene, benzo[*g*,*h*,*i*]perylene, and indeno[1,2,3-*cd*]pyren (Kemakta & Karolinska Institutet, 2017). These three groups of PAH together are often referred to as PAH-16 (Zhao, et al., 2013; Kemakta & Karolinska Institutet, 2017).

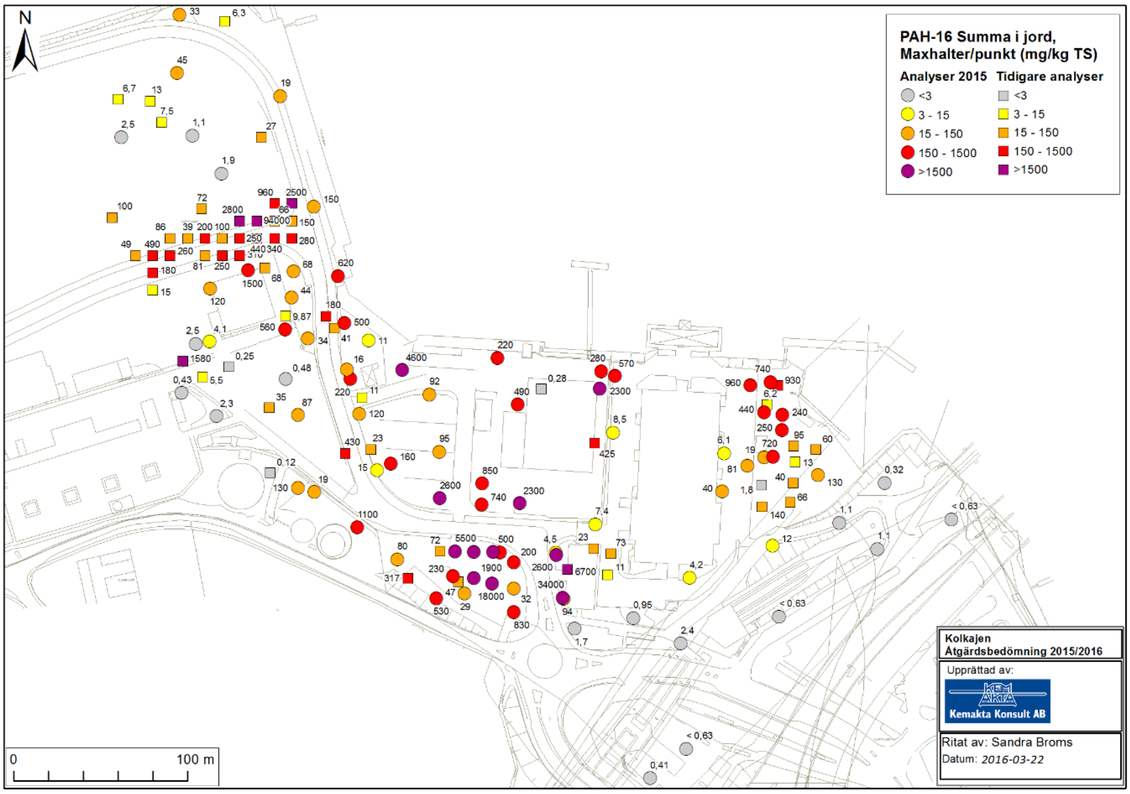


*Figure 7. Map of the Kolkajen-Ropsten site with measured PAH concentrations expressed as max value in each point in mg/kg TS (from Kemakta, 2016).*

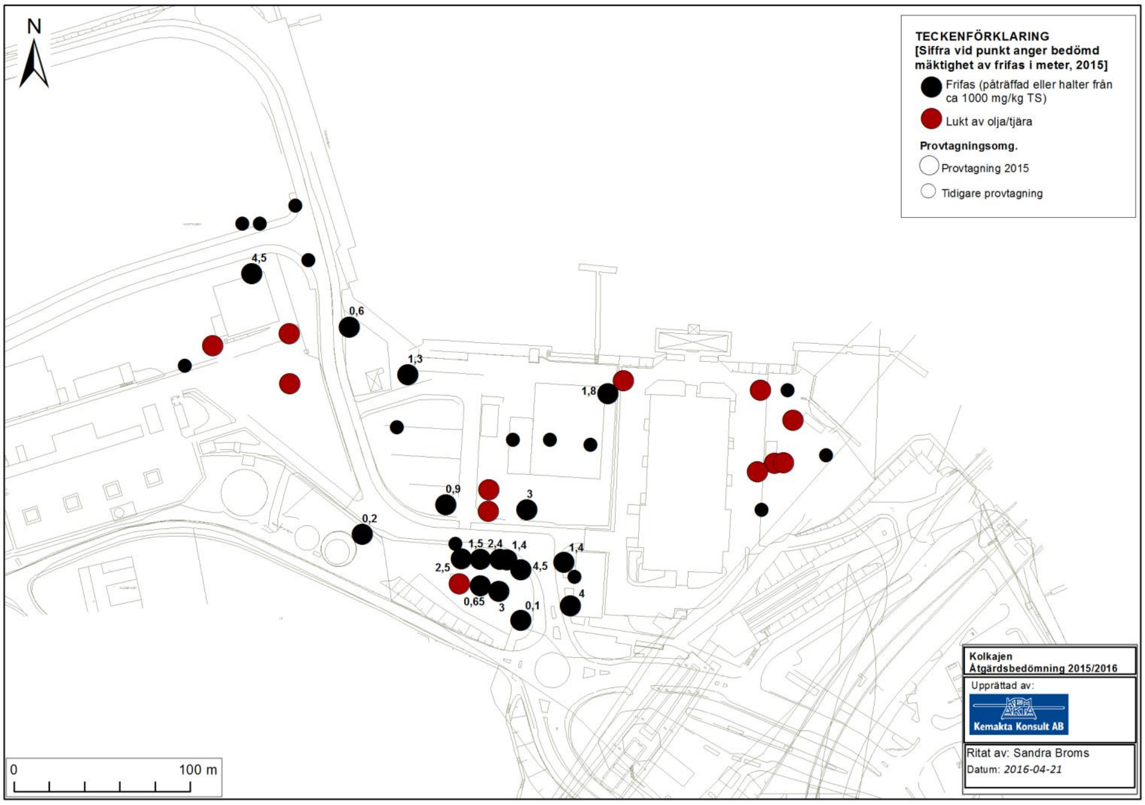


*Figure 8. Map of the Kolkajen-Ropsten site with regard to oil and tar presence in free phase. Black dots indicate locations with contaminants in free phase, either free phase was found or concentrations above ~1000 mg/kg TS were measured, which indicates that there is free phase present. Red dots show the locations where smell of oil/tar was registered. The numbers indicate the depth at which they were measured. From Kemakta (2016).*

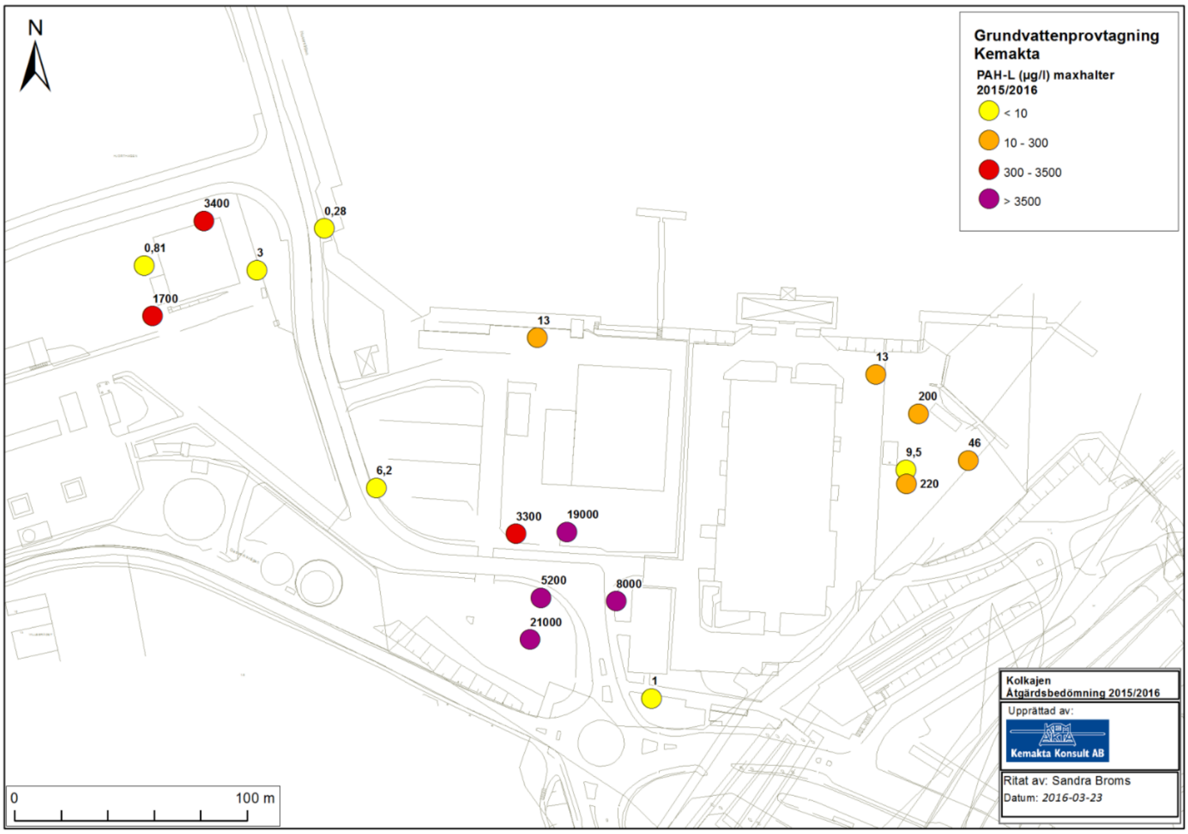


*Figure 9. Map of Kolkajen-Ropsten site, with the highest measured PAH concentrations shown in µg/l (from Kemakta, 2016).*

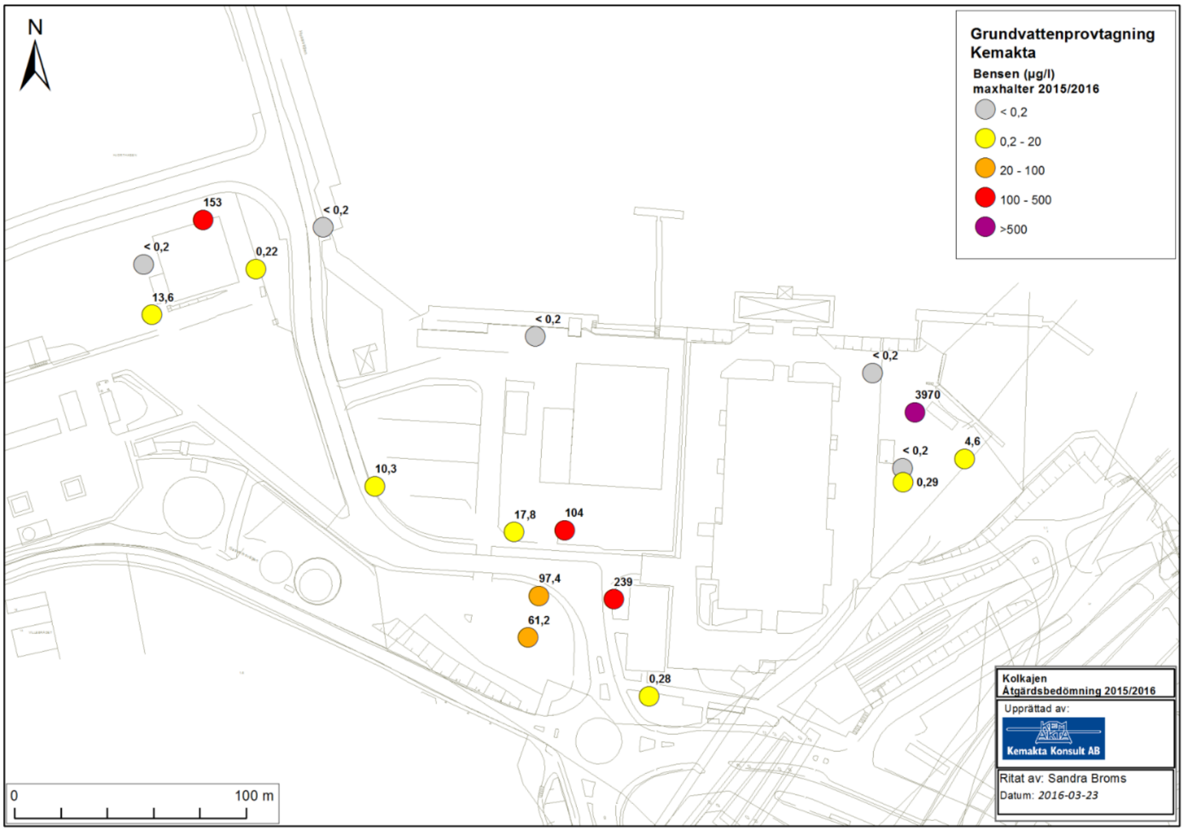


*Figure 10. Map of Kolkajen-Ropsten site with the highest measured benzene concentrations in µg/l (from Kemakta, 2016).*

### 4.1.3. Sediments and surface water contamination

In the sediments, oil (different aliphatic and aromatic compounds), copper and mercury in high concentrations were found. In some sub-areas, primarily close to the old production site or in areas where tar conducts had their outlet, tar in free phase was observed and very high concentrations measured. The contamination in the sediments in Lilla Värtan, just outside the site, presented the same pollutants as the contaminated area, with high levels of polycyclic aromatic hydrocarbons (PAH). It was concluded that there is a need to remediate the sediments, in particular to reduce the risk of further dispersion to the surrounding waters in Lilla Värtan. There, contamination may lead to an increased health risk in coastal areas, both via skin contact with sediment and via evaporation and penetration into buildings. However, sediments remediation won't be discussed in this thesis, and therefore further information is not presented.

Regarding surface water, no specific guidelines values were present on acceptable levels of PAH contamination (Kemakta, 2016). USEPA states that no PAH should be detected in water to ensure consumers health (USEPA, 2000), but in the risk assessment conducted by Kemakta, 2016, guidelines values for drinking water were sued to assess the severity of surface water contamination. Drinking water standards are not available for aliphatic and aromatic substances, and the levels specified by the Swedish Environmental Protection Agency (2009) and SPI (2011) indicate levels above which the water starts to taste and smell. The measured PAH concentration do not exceed the guidelines values (Kemakta, 2016), which means that health risks are unlikely to occur when bathing in the area, even if the levels against which the concentrations were compared were very conservative (Kemakta, 2016). Sediments remediation is expected to diminish even further the contamination of surface water (Kemakta, 2016).

## 4.2. Contaminants

In coal-tar contaminated soils, tar residuals (mostly PAH and petroleum hydrocarbons) are usually the main pollutants (Luthy, et al., 1994). Tar residuals usually come from volatile component of bituminous coals in coal carbonization, from oil gas processes and from the cracking of enriching oils in carburated water gas production, and they are organic liquids, denser than water and with various physical-chemical properties (Luthy, et al., 1994). However, up to 200 chemicals are part of this family, therefore the composition of the residuals depends on the coal tar from which they were produced and their toxicity depends on the chemicals present (Forsey, 2004).

Being DNAPLs (Dense Non-Aqueous Phase Liquids), tar migrates downwards in the soil due to the gravity force, until it finds a low permeability layer that cannot penetrate, so it often reaches the groundwater table. Moreover, NAPLs spills often result in subsurface accumulation, that can then be a contamination source for groundwater (Sauer & Costa, 2003). Tar can then slowly dissolve and create a plume in the groundwater, but a part of it will remain as a NAPL (the amount depends on the age of the contamination and on tar properties), mostly trapped in the pores acting as a contamination source (Sauer & Costa, 2003).

In the following sections, the main contaminants found at Kolkajen-Ropsten site will be briefly described.

### 4.2.1. Polycyclic aromatic hydrocarbons (PAH)

PAH is one of the most extensive and assorted group of organic contaminants existing. These contaminants are composed by fused benzene rings and they are recognized as carcinogenic and mutagenic chemicals (Chen, et al., 2015), which ecotoxicity is proven on aquatic life and terrestrial invertebrates (Abdel-Shafy & Mansour, 2016). They are ubiquitous, due to the fact that are emitted from natural and anthropogenic sources (Wilcke, 2007): in fact, they are the by-products of incomplete combustion or pyrolysis of organic matter (Rivas, 2006).

PAH contamination in the soil is usually dominated by two major sources: atmospheric deposition and background concentration (Wilcke, 2007), but in industrial contaminated soils the contamination is often due to spills and mishandling of materials/liquids containing PAH (Luthy, et al., 1994). In the soil, PAH tend to adhere to particulates and on the organic fractions of the solids and due to their adsorption potential, they can retain in the soil matrix for a long time and then leaching in groundwater or water bodies nearby (Chung, et al., 2007).

It is difficult, if not almost impossible, to establish a threshold value for PAH adverse health effects, because of the lack of dose-response data on carcinogenicity and because they are often present in mixtures of different compounds (up to hundreds). Moreover, they contemporary can have synergistic or/and antagonistic effects with other factors that population may be exposed to (Chen & Liao, 2006). The US National Institute for Occupational Safety and Health (NIOSH) has set as workplace exposure limit for PAH 0.1 of $mg/m^3$, which is the lowest detectable concentration for coal tar pitch volatile agents (Abdel-Shafy & Mansour, 2016). According to USEPA, the concentration of PAH in water should be non-detectable in order to protect human health from the carcinogenic effects of exposure to these compounds (USEPA, 2000). The most carcinogenic of the PAH is benzo(a)pyrene (BaP), and often the guidelines refer to equivalent of this compound in the form of BaP TPE (benzo(a)pyrene total potency equivalents) (Abdel-Shafy & Mansour, 2016). According to the Canadian soil quality guidelines, the concentration of PAH should not be higher than 0.6 $mg_{BaP\ TPE}/kg_{soil}$ for direct contact with soil based on an incremental lifetime cancer risk (ILCR) of 1 in 1 000 000, and 5.3 $mg_{BaP\ TPE}/kg_{soil}$ based on an ILCR of 1 in 100 000 (CCEE, 2010). Regarding groundwater protection, Canadian Council of Ministers of the Environment (CCEE) stated that the same guidelines for soil apply to groundwater.

In Sweden, the sixteen most toxic PAH are often divided in 3 groups, according to their molecular weight: PAH-L (light), PAH-M (medium) and PAH-H (heavy) (Kemakta & Karolinska Institut, 2017). Kemakta & Karolinska Institut, 2017, calculated some general guidelines for PAH in the soil, divided in PAH-L, PAH-M and PAH-H: depending if the land use is considered sensitive or not, light PAH cannot be measured in concentrations above 3 or 15 mg/kg TS, PAH-M cannot exceed 3.5 or 20 mg/kg TS and PAH-H cannot have values above 1 or 10 mg/kg TS. There are not guidelines for PAH contamination in groundwater from SEPA, but the site-specific limits were calculated according to the risk of spreading to surface water and to spread in indoor air, as shown in Table 7.

Among the PAH measured at the site, naphthalene presence was widespread. It is the simplest PAH, which chemical formula is $C_{10}H_8$. Its structure consists of a pair of fused benzene rings. It is classified as potentially carcinogenic, with the potential to damage or disrupt red blood cells and cause cataracts in humans (IARC, 2002). Naphthalene presence is common in contaminated sites (Badr, et al., 2004).

### 4.2.2. Benzene

Benzene is a colourless liquid cyclic aromatic hydrocarbon, which chemical formula is $C_6H_6$. It has a slow degradation rate (compared to PAH) and rapid evaporation, it is highly flammable and it has low solubility in water but it is miscible with most organic solvents (Calza, et al., 2015). It is carcinogenic, and human exposition to benzene is mostly due to inhalation (Calza, et al., 2015). This compound did not show highly acute toxicity in experimental animals, while chronic exposure could result in haematotoxicity, immunotoxicity and carcinogenicity both in animals and humans (EPHC, 2003).

United Kingdom Environment Agency indicates that benzene concentration in soil should not exceed 0.33 $mg/kg_{DW}$ for residential use, 0.07 $mg/kg_{DW}$ for allotment and 95 $mg/kg_{DW}$ for commercial use (Environment Agency, 2009), while no Swedish guidelines are present. No groundwater guidelines are present in Sweden, and most countries refer to drinking water values: as an example, USEPA indicates a maximum contaminant level (MCL) for drinking water of 0.005 mg/L, with potential health effects of anaemia, decrease in blood platelets, and increased risk of cancer (USEPA, 2009). USEPA also sets 0.004 mg/$kg_{BW}$/day as reference dose for chronic oral exposure and 0.003 ppm for chronic inhalation exposure and 0.009 ppm for acute inhalation (USEPA, 2009).

### 4.2.3. Petroleum hydrocarbons

Petroleum hydrocarbons is a family of contaminants which comprises complex mixtures of organic compounds with different molecular weights (Megharaj, et al., 1999). They are often found in both contaminated soil and groundwater and their accumulation in humans, animals and plants may cause mutations or death (Das & Chandran, 2011). Also, some of the metabolic compounds of the petroleum hydrocarbons contribute to biota toxicity (Tang, et al., 2011).

In the past, remediation of these contaminants has been documented using physical, chemical and biological alternatives (Okoh & Trejo-Hernandez, 2006). Since the concern related to the presence of these contaminants on-site was lower than for PAH or benzene, no site-specific guidelines or remediation goals were set.

## 4.3. Remediation techniques considered for the site

A big part of the contaminated soil was being and will be excavated to make room for foundations, roads, installations and all the facilities necessary when constructing new buildings. These masses will be excavated and treated off site at a treatment area managed by the municipality. However, the focus of this thesis is on the contamination at greater depths, that in some points can reach depths of up to 20 meters (Kemakta, 2016), and in those places where the contamination is present but excavation would be difficult or too expensive. For those areas, in-situ remediation techniques are deemed necessary. In the following sections, only the techniques that were initially assessed to be potentially used in the site are presented and they are summarized in Table 8.

*Table 8. Techniques that were initially studied and/or implemented as pilot tests.*

| Technique | Type | Comments |
|---|---|---|
| Excavation/landfilling | Ex-situ | Possibly followed by in-situ techniques |
| ISCO | In-situ | Tested with two different types of $H_2O_2$ and persulfate |
| Bioremediation | In -situ | Tested with two different kind of calcium peroxide |
| Soil flushing | In-situ | Tested |
| Thermal treatment | In-situ | In-situ thermal desorption (ISTD) or in-situ thermal stabilization (ISTS) |
| Solidification/Stabilization | In-situ | Considered to be coupled with other techniques |

### 4.3.1. Ex-situ remediation techniques considered for the Kolkajen site

At Kolkajen Site, the ex-situ remediation techniques that has been evaluated with SCORE is excavation of the shallow soil (at different depths) followed by in-situ techniques. This method involves the excavation of the soil with excavators and its transport to landfill(s), either by truck or boat. Also, this technique implies that the excavated masses have to be replaced with pristine soil, if needed.

### 4.3.2. In-situ remediation techniques considered for the Kolkajen site

The in-situ remediation techniques considered for Kolkajen site are in-situ chemical oxidation, bioremediation, soil flushing, solidification and stabilization and thermal treatment and their characteristics have already been described in section 2.6. The site-specific features of each of them are instead presented in this chapter.

*In-situ chemical oxidation*
Initially, at Kolkajen site, bulk $H_2O_2$ has been tested. However, the injection of bulk $H_2O_2$ resulted in a dramatic and quick reaction time that was considered dangerous for the workers safety point of view. Therefore, a new test was carried out mixing bulk $H_2O_2$ with $C_6H_8O_7$ (citric acid) in order to slow down the oxidising reaction. The chemicals were provided by Akzo Nobel. A total amount of 150 litres of the solution were injected every half meter from a depth of about 4 to 16 meters below ground surface, in every direction. Peroxide and citric acid were mixed right before injection, with a ratio of about 9 to 1 of peroxide.

Another reagent was tested, RegenOx by Regenesis, a slow release variety of $H_2O_2$. This ISCO reagent is composed by two parts: (1) solid sodium percarbonate based alkaline oxidant and (2) liquid mixture of sodium silicates, silica gel and ferrous sulphate and effective on treating BTEX, petroleum hydrocarbons, chlorinated solvents, PAH and aromatic compounds (Regenesis, 2017a).

Regarding the tests carried out at the site with the use of persulfate, PersulfOx by Regenesis was chosen. This solution consists of sodium persulfate and a catalyst that activates it, and it is effective in treating the same contaminants as RegenOx (Regenesis, 2017b). The oxidation process which the contaminants undergo is called ‘surface mediated oxidation’, because oxidants and contaminants react on a silica-based microscopic surfaces (Regenesis, 2017b).

*Bioremediation*
At the Kolkajen site, ORC Advanced by Regenesis was tested. It is a calcium oxy-hydroxide based oxygen release compound. When in contact with groundwater, this compound produces a controlled release of molecular oxygen for periods up to 12 months and the typical contaminants on which it is effective comprehend BTEX, coal tar residuals, petroleum hydrocarbons, some chlorinated solvents, PAH, and aromatic compounds (Regenesis, 2017c). At the site, it was applied through slurry mixture direct-placement into boreholes.

PermeOx by PeroxyChem was also tested at the site, which is a calcium peroxide compound, available in powder or granular form. It contains ca. 18% active oxygen, and it can release oxygen for up to 350 days. Case studies showed that it is effective on petroleum hydrocarbons, BTEX, vinyl chloride and naphthalene (PeroxyChem, 2017) and, at the site, it was applied through direct injection with slurry.

*Soil flushing*
At the Kolkajen site, soil flushing was tested using PetroCleanze™. It is a two-part reagent, which properties increase the desorption rates of hydrocarbons bound in saturated soils. It is not a surfactant, instead it creates surfactants when in place, enhancing the contaminants removal. It is designed to be used on petroleum hydrocarbons, BTEX, chlorinated solvents, PAH and aromatic compounds (Regenesis, 2017d). The fluid composed of water, the reagent and the contaminants would be then pumped and treated in a WWTP managed by the municipality.

*In-situ thermal treatment*
At the Kolkajen site, Thermal Conduction Heating (TCH or ISTD) was the thermal treatment method initially considered.
In order to use this technology, it was important to gather information about the groundwater level at the site, because heating of water saturated soils may cause high thermal losses, and thus lowering the groundwater table could have been needed to ensure the heating of the subsurface.

Regarding PAH contamination, the use of thermal treatment methods might be limited by the fact that some PAH will be left in the ground. Literature suggests that a common strategy involves the heating of the surfaces at temperatures close to 70-100 °C, in order to evaporate the lightest fractions and reduce the viscosity of the tar residuals enough to pump them out (Kemakta, 2016). However, for the heavy PAH to evaporate, temperatures up to 550°C might be required, posing some issues related to the cost of this solution when considering also to lower the groundwater level, necessary to reach such high temperatures (Kemakta, 2016). In-situ thermal stabilization was then considered a good option, in order to treat the most mobile and volatile contaminants that could intrude the buildings and to leave an asphalt-like material in the soil that should avoid the spreading of the contamination.

*Stabilization/Solidification*

At Kolkajen site, stabilization/solidification was considered to be implemented using lime and cement as binding agents to stabilize the ground and to activate persulfate to treat the contaminants. This was planned to be preceded by excavation of the shallow contamination and followed by ISCO or bioremediation of the deepest soil.

## 4.4. Results of the Pilot Tests and Remediation Techniques Considered for Further Studies

Some of the different in-situ techniques were tested with pilot plants on-site (ISCO, bioremediation and soil flushing). The results of these tests helped to rule out some of the techniques and to understand which ones were the most promising. According to the data provided by RGS Nordic, the company in charge for the pilot testing, ISCO with persulfate and bioremediation were the most promising in-situ techniques (Appendix I). ISCO was then considered to be used for the deepest part of the soil or in combination with S/S. Bioremediation was considered to be used coupled with other techniques, such as excavation and S/S. Thermal remediation was also considered to be an effective solution for the site, especially for the parts of difficult access or that needed to be remediated quickly, although the cost of this remedial action was considered to be potentially substantial.

However, due to the differences in the contamination and in the geology of the various parts of the site, different remedial actions might be used together. In spite of this, some simplifications were needed in order to properly carry out the sustainability assessment with the information available at the time this thesis was realized (see Section 5).

# 5. SCORE analysis of the case-study site

## 5.1. Conceptual site

Due to the inherent difficulties related to the real site, some simplifications and assumptions needed to be made. The first and most important concerned the geology of the site: the real geology was very complex and properties such as groundwater table elevation, bedrock depth and clay depth varied from area to area in the site, and consequently the contamination depth and contaminants concentration. Therefore, the site was idealized as shown in Figure 11. Three different types of soil were assumed to be present at different depth, homogeneous in each layer: the topsoil consisting of so-called 'filling material' for the first meter, clay from 1 to 5 meters below the ground level and a mix of sand and gravel in the remaining part of the soil, with the groundwater table stable at four meters below the ground level. The volume of the soil to be remediated was estimated to be 75 000 $m^3$ (Kemakta, 2016) and an average depth of the contamination was estimated to reach 13 meters below ground level, after consultation with experts involved in the project. Regarding the physical boundaries of the site, soil and groundwater were considered to be present on-site, while surface water and sediments only off-site.

The concentration of the contaminants was assumed to be constant in every part of the site, using the mean values of the measurements at the site shown in Table 6 and 7. In addition, the site was considered to have only old dismissed industrial buildings on the surface, and apart from that to be free from obstacles that could prevent the use of certain techniques, with a surface area of 5770 $m^2$. The soil density at the site was estimated to be 1.7 $t/m^3$ (Kemakta, 2016). In order to properly landfill the (eventual) excavated contaminated soil excavated, it was divided into soil considered 'non-hazardous waste' (50%), soil considered 'hazardous waste' (35%) and soil considered 'hazardous waste with contaminants in free phase' (15%) (Kemakta, 2016). This division of the soil influences where it can be landfilled and its cost. Also, due to the excavation already going on at the site, it was estimated that only 80% of the excavated soil needs to be replaced with pristine soil from an external site (Kemakta, 2016).

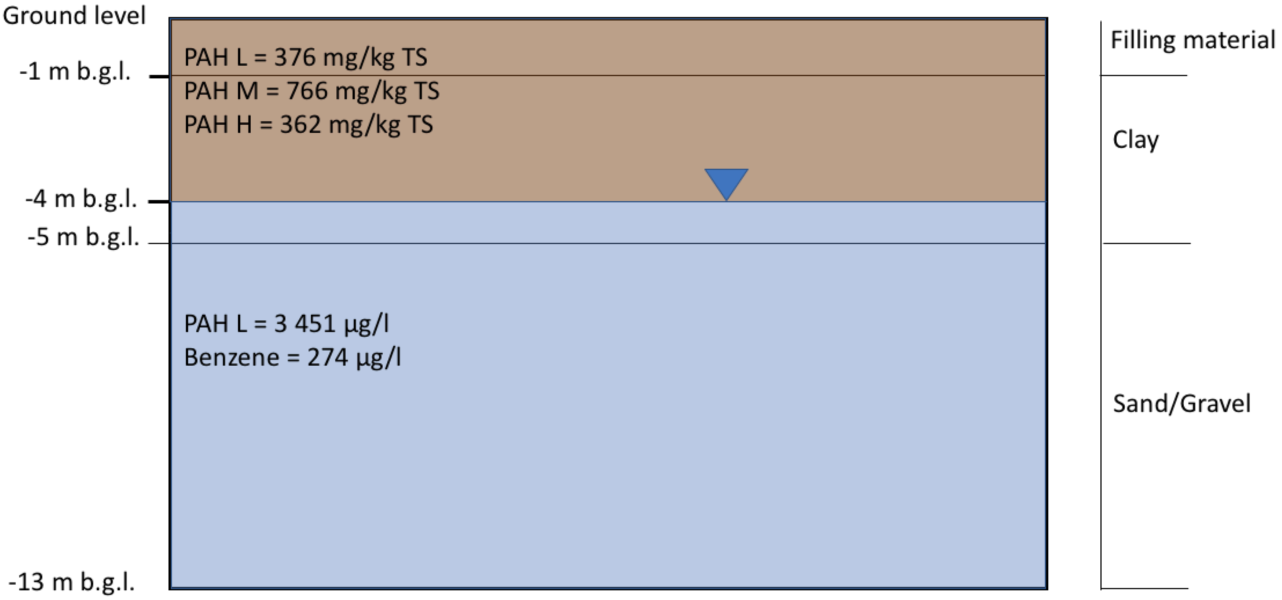


*Figure 11. Conceptual model of the site.*

## 5.2. Reference alternative and boundaries of the SCORE analysis

In SCORE, it is the team that evaluates the alternatives that decides what the reference alternative is (Rosén, et al., 2015). In this case, 'no action' has been selected as a reference alternative, meaning

that all the remediation alternatives will be evaluated against a situation where nothing is done in order to decrease the risks to humans, the environment at the site and its surroundings.
At the Kolkajen-Ropsten site, ‘no action’ means that the contaminants, mainly PAH, will remain in the soil, where they will pose a health risk for the eventual residents in the new houses. Furthermore, the contaminants will continue to leach to the groundwater and may also spread further to surface water. This could cause environmental damage, as much as a consistent loss of money for the municipality and the companies that already invested resources in the project to redevelop this part of the city. In fact, it would be very unlikely that permits to build apartments and other buildings would be given, since a concrete risk for people’s health exists at this site.

However, Kolkajen-Ropsten project is part of the bigger project for Norra Djurgårdsstaden (as shown in Figure 5 in Section 4), and it has to be considered that extensive excavation and working are already present in the areas nearby the site also in the ‘no action’ scenario. This feature is important when considering the score of some social and environmental criteria.

## 5.3. Remediation alternatives

Table 9 shows the alternatives considered for Kolkajen site that have been evaluated in SCORE. All the alternatives were analysed in SCORE for two transport scenarios: (a) with transport of the contaminated soil to a landfill by boat (after being transported by truck to a harbour) and (b) transport of the contaminated soil to a landfill by truck.

*Table 9. Remedial alternatives considered for Kolkajen-Ropsten site.*

| Alternative | Technique |
|---|---|
| No action | - |
| Alternative 1 | Excavation of the first 5 meters of soil + ISCO with persulfate |
| Alternative 2 | Excavation of the first meter of soil + S/S + ISCO with persulfate |
| Alternative 3 | Excavation of the first 5 meters of soil + bioremediation |
| Alternative 4 | Excavation of the first meter of soil + S/S + bioremediation |
| Alternative 5 | Excavation of the first 5 meters of soil + ISTS |

### 5.3.1. Assumptions related to the remediation alternatives

A number of assumptions were necessary when defining the remediation alternatives, summarised in Table 10. The remedial alternatives were modelled and assessed in SCORE as only one alternative at a time was used to remediate the whole site, while in the reality it might be possible that different alternatives would be used for different parts of the site, depending on the time needed to remediate and constraints to use some techniques in certain areas of the site. The most important assumption common to all the alternatives was that there were no constraints with the geology of the site in the application of the techniques and that each alternative was able to reduce the contamination to the clean-up goals. These assumptions are commented more in depth in Section 7.

Also, assumptions were made regarding the different technologies in the alternatives:

- ISCO was tested twice at the site, first with a pilot test as for all the other techniques and then with a second pilot test treating a bigger contaminated volume (approx. 1/10 of the conceptual site). In this project, the amount of chemicals to be used in the alternatives involving ISCO was scaled up from the amount used in the second pilot test, where 2.45 kg of PersulfOx were used to treat each ton of soil. The price was scaled up from the report with the prices for the second pilot test. The time needed for this technology to effectively treat the contamination was estimated to range between 9 and 12 months in the risk assessment report by Kemakta, 2016.

- Regarding bioremediation, the amount of ORC solution needed to effectively treat the contamination and the price of this solution were estimated from the first pilot test, where 0.28 kg of ORC solution was used to successfully treat each ton of soil, therefore the uncertainties related to the amount of chemicals to use is slightly higher than for ISCO, because the information taken from the second pilot test were more precise, due to the fact that the quantity of materials to be used were decided according to the results of the first one. Moreover, no site-specific information about the time needed for this solution to effectively treat the contamination was given, and values from the literature were used: looking at the case studies present on the website of the Federal Remediation Technologies Roundtable (FRTR, 2018), bioremediation with the use of ORC solutions can take from months to years to efficiently treat PAH.

- Solidification/stabilization technique was still in the stage of early testing by the time this project was completed, therefore the amount of lime/cement and persulfate needed were estimated from laboratories data: a minimum of 6% (of the soil weight) of lime/cement solution (50/50) was injected with a maximum of 3% (of the soil weight) of persulfate. The price of this technology was estimated according to literature data and feedback from experts, but its reliability depends on the uncertainties related to the quantities of materials used for it. The implementation of S/S itself is relatively fast (Holm, et al., 2007), but since this technology was used in alternatives comprising also other methods, the overall time needed for remediation depended more on those.

- In-situ thermal treatment is known for being a fast remediation option (Stegemeier & Vinegar, 2001), but the energy requirements for this technique were not deeply investigated yet at the time this project was carried out, therefore high uncertainties were linked to it. The same problem was encountered when trying to define the price of this solution, but the uncertainties were lower than in the case of the energy requirements, because various case studies mentioning the cost of this solution were found (FRTR, 2018).

- Price and time needed for excavation were well defined in the report from Kemakta (2016), but uncertainties were related to the landfill to dispose the excavated soil and the site to get the pristine soil from.

*Table 10. Main assumptions and relative uncertainties for each RA.*

| Technology | Main assumption(s) | Uncertainties |
|---|---|---|
| ISCO | Amount of persulfate needed | Low |
| | Time needed for the remediation | Low |
| | Price | Low |
| Bioremediation | Amount of ORC solution needed | Medium |
| | Time needed for the remediation | Medium |
| | Price | Medium |
| S/S | Amount of lime, cement and persulfate needed | Medium |
| | Time needed for the remediation | Low |
| | Price | Medium |
| ISTS | Energy requirements | High |
| | Time needed for the remediation | Low |
| | Price | Medium |
| Excavation | Landfill for soil disposal | Medium |
| | Site used for pristine soil | High |

| | | |
|---|---|---|
| All the alternatives | All the RA are able to reduce the contamination to site-specific remediation goals | Low |
| | All the techniques are suitable for the site (no constraints due to surface or geology of the site) | Low for all the RA, but medium for ISTS. |

*Transport of the contaminated soil: scenarios a and b*

Ecoloop, the consultancy working on defining which landfill disposal scenario would be the most sustainable, provided data about what the options were for landfilling: in order to diminish the problems related to emissions from trucks and trucks passing in the city, transport by boat was considered as the main option. Therefore, two scenarios were decided to be analysed in SCORE: in the first one (transport scenario a), the soil was transported to a harbour close to the site (no more than 10km away) and from there transported to a landfill in the coast (no farer away than 250 km – 200km was the distance recommended by the consultancy to use in SimaPro) and in the second one a landfill 40km away from the site was considered, with the transport of the soil carried out by trucks (transport scenario b). Unfortunately, no precise data were given about from which site the pristine soil would have been taken, therefore a distance of 80km covered by truck was assumed. Detail of the transport scenarios are given in Appendix II.

## 5.4. Environmental criteria

Until now, SCORE method has been used to compare remediation alternatives involving excavation and landfill disposal, with (eventual) treatment of the soil on-site. Because these techniques involved similar technologies, the impacts and emissions were similar and comparable, and it has been straightforward the way the environmental criteria were scored. Instead, to compare and hence score using the same rating scale techniques that use different technologies, such as in-situ techniques and excavation, the situation is different because their effects on the environment are different and depend on different factors (i.e. type of chemical used, need for energy, etc.).

Therefore, more precise information and data were needed in order to compare the different alternatives. The first step consisted in assessing which were the major causes of environmental impacts for each technique, both before and during the remediation processes. With this information at hand, it was possible to score some criteria in a semi-quantitative way and some others in a quantitative way, modelling the processes that composed each remedial action in SimaPro software. The application of these passages is described in the next sections.

### 5.4.1. Selection and scoring of the environmental criteria

The relevant criteria in each domain were chosen depending on their importance related to Kolkajen site and to what was considered on and off-site, as described in Section 5.1.

Table 11 shows the sub-subcriteria used to score the environmental criteria, while the actual scoring process was already described in the methodology and the application is shown in the next sections. Some criteria or sub-criteria were not taken into account due to their relatively low importance for the specific site and therefore are not shown in the table.

*Table 11. Criteria relevant for the case study and their division in subcriteria and sub-subcriteria.*

| Key criteria | Sub-criteria | New sub-subcriteria |
|---|---|---|
| E1: Soil | Ecotoxicological risk RA on-site | Risk of spreading of chemical or contamination |
| | | Risk of hazardous by-products formation |

| | | |
|---|---|---|
| | | Other environmental effects |
| | Ecotoxicological risk SC on-site | |
| | Soil functions RA on-site | |
| E3: Groundwater | Groundwater RA on-site | Risk of spreading of chemical or contamination |
| | | Risk of hazardous by-products formation |
| | | Other environmental effects |
| | Groundwater SC on-site | |
| E4: Surface water | Surface water RA off-site | Risk of spreading of chemical or contamination |
| | | Risk of hazardous by-products formation |
| | | Other environmental effects |
| | Surface water SC off-site | |
| E6: Air | Air RA off-site | Global warming |
| | | Ozone formation |
| | | Terrestrial acidification |
| | | Fine particulate matter formation |
| E7: Non-renewable natural resources | Natural resources RA off-site | Pristine soil |
| | | Fossil resource scarcity |
| | | Water consumption |
| E8: Non-recyclable Waste Generation | Waste RA off-site | |

### 5.4.2. Environmental impacts of the selected alternatives

*ISCO, S/S and bioremediation*

The drivers of the environmental impacts of the alternatives ISCO, S/S and bioremediation were identified as production and transport of the chemicals (Cadotte, et al., 2007). Impacts during the production processes were investigated looking for data about the chemical composition of each product (Table 12) and then using the data to model the environmental impacts of their most common production processes in SimaPro.

*Table 12. Composition of the chemicals used for the in-situ techniques.*

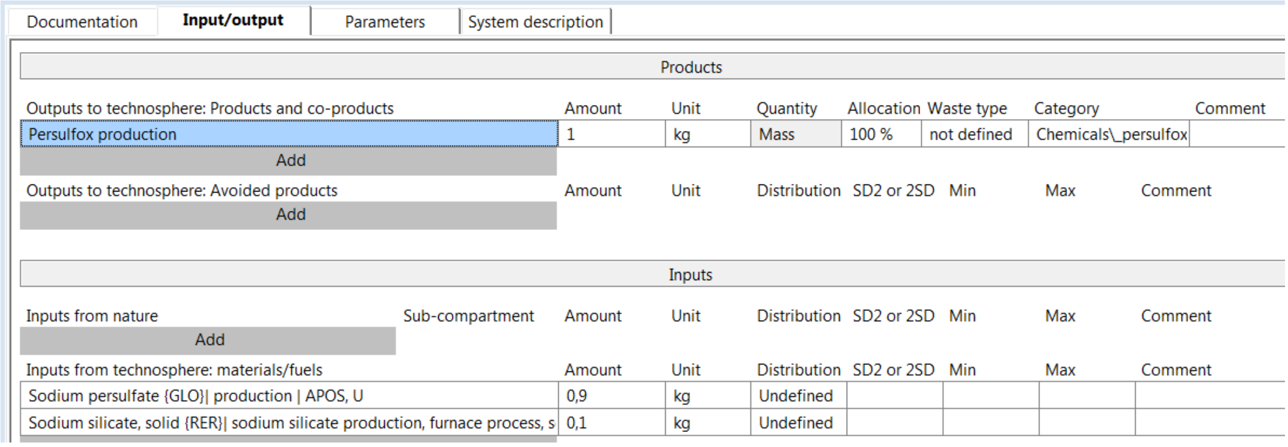
| | PersulfOx | S/S mix | PermeOx |
|---|---|---|---|
| Composition | Sodium persulfate ≥ 90%, silicic acid ≤ 10% | Cement 33%, lime 33%, persulfate 33% | RegenOx part A 42% (Sodium Carbonate Peroxyhydrate), ORC Advanced 58% (Calcium peroxide ≥ 75%, calcium hydroxide ≤ 25%) |

Impacts during transport were assessed considering the distance and means of transport of the contaminants from the production plant to the site. The Regenesis products (PersulfOx, RegenOx part A and ORC advanced) have been shipped to Stockholm by boat from UK, where the production plant is located in Bath, therefore the transport considered was: (1) Bath-Portsmouth, by truck, (2) Portsmouth-Stockholm by cargo ship. The route Bath-Portsmouth port was calculated to be 132 km and the second travel distance was calculated using Voyage Planner (MarineTraffic, 2018) and it resulted in 1384 nautical miles, equal to 2563 km, covered with a cargo ship.

Stabilization/solidification also has the main impacts in the production and transport of the chemicals to the contaminated site (Hou, et al., 2016). No information was provided on the producers of cement, lime or persulfate therefore it was assumed that the persulfate would undergo the same processes as PersulfOx (even if the persulfate used for this technology was from a different - cheaper- brand), and that lime/cement mixture was shipped from a facility located in an area 100 km far from the site, considered a fair assumption due to the fact that some producers were present in the area.

The impacts of the production and transport processes were calculated using SimaPro software, where the functional unit chosen was the whole conceptualized contaminated site (i.e. the action needed to remediate the contaminated soil to meet the remediation goals). Figures 12 and 13 show the process to model PersulfOx production and transport for alternatives 1 and 2, whereas information for the other alternatives are shown in Appendix III.
First, the production of the chemical is added, (Figure 12). Here the energy needed to actually obtain PersulfOx from the two chemicals was disregarded.
Thereafter, ‘Transport of 1 kg of PersulfOx’ was added as a new material process (Figure 13). The data about the distance between the production plant and Stockholm is described above.

The following figures (Figures 12 to 16, and Appendix III) show the processes selected in SimaPro to model the different parts of the remedial alternatives, so that the steps to build the streamlined LCA are clear and reproducible.



Products

| Outputs to technosphere: Products and co-products | Amount | Unit | Quantity | Allocation | Waste type | Category | Comment |
|---|---|---|---|---|---|---|---|
| Persulfox production | 1 | kg | Mass | 100 % | not defined | Chemicals_persulfox | |

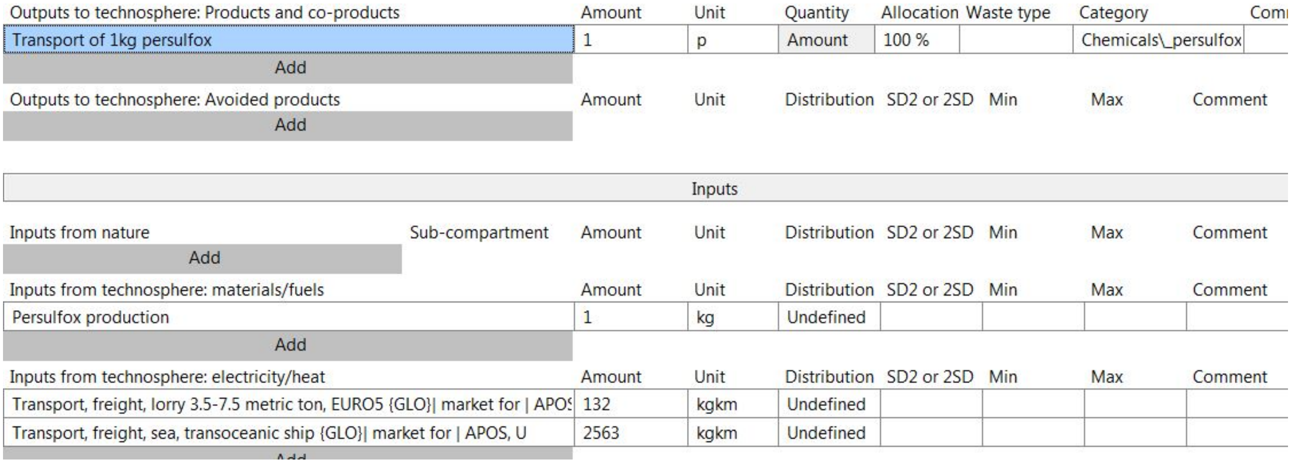
| Outputs to technosphere: Avoided products | Amount | Unit | Distribution | SD2 or 2SD | Min | Max | Comment |
|---|---|---|---|---|---|---|---|

Inputs

| Inputs from nature | Sub-compartment | Amount | Unit | Distribution | SD2 or 2SD | Min | Max | Comment |
|---|---|---|---|---|---|---|---|---|

| Inputs from technosphere: materials/fuels | Amount | Unit | Distribution | SD2 or 2SD | Min | Max | Comment |
|---|---|---|---|---|---|---|---|
| Sodium persulfate {GLO}\| production \| APOS, U | 0,9 | kg | Undefined | | | | |
| Sodium silicate, solid {RER}\| sodium silicate production, furnace process, s | 0,1 | kg | Undefined | | | | |

*Figure 12. PersulfOx production in SimaPro. The process is modelled for 1kg of product.*



| Outputs to technosphere: Products and co-products | Amount | Unit | Quantity | Allocation | Waste type | Category | Comı |
|---|---|---|---|---|---|---|---|
| Transport of 1kg persulfox | 1 | p | Amount | 100 % | | Chemicals_persulfox | |
| Add | | | | | | | |

| Outputs to technosphere: Avoided products | Amount | Unit | Distribution | SD2 or 2SD | Min | Max | Comment |
|---|---|---|---|---|---|---|---|
| Add | | | | | | | |

Inputs

| Inputs from nature | Sub-compartment | Amount | Unit | Distribution | SD2 or 2SD | Min | Max | Comment |
|---|---|---|---|---|---|---|---|---|
| Add | | | | | | | | |

| Inputs from technosphere: materials/fuels | Amount | Unit | Distribution | SD2 or 2SD | Min | Max | Comment |
|---|---|---|---|---|---|---|---|
| Persulfox production | 1 | kg | Undefined | | | | |
| Add | | | | | | | |

| Inputs from technosphere: electricity/heat | Amount | Unit | Distribution | SD2 or 2SD | Min | Max | Comment |
|---|---|---|---|---|---|---|---|
| Transport, freight, lorry 3.5-7.5 metric ton, EURO5 {GLO}\| market for \| APOS | 132 | kgkm | Undefined | | | | |
| Transport, freight, sea, transoceanic ship {GLO}\| market for \| APOS, U | 2563 | kgkm | Undefined | | | | |

*Figure 13. Modelling of PersulfOx transport in SimaPro. The process is modelled for 1 kg of product.*

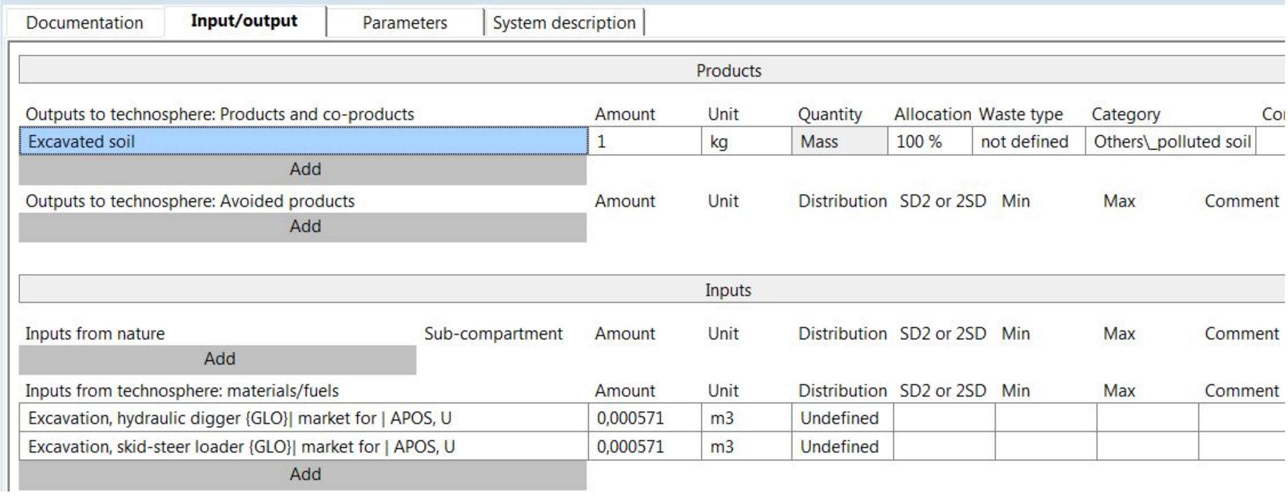
*In-situ thermal stabilization*

Since the environmental impacts of the thermal treatment were assessed to be mainly due to the energy consumption, in SimaPro this process was modelled taking only this parameter into account. SimaPro calculations for this alternative are shown in Appendix III.

*Alternatives involving excavation and landfilling of the contaminated soil*

The main environmental impacts of excavation and landfilling were previously identified as the excavation and transport of the contaminated and pristine (filling) soil, as already described previously. These processes were modelled in SimaPro by first creating a process for the excavation, as shown in Figure 14, then modelling the transport of the soil to the landfill and finally modelling the transport of pristine soil (filling material) to the site, Figure 15. In the calculations, trucks/ships or other means of material transport were considered to be loaded only one way, and empty on the return.

For excavation combined with an in-situ technique (e.g. excavation + ISCO using PermeOx), the overall impact was calculated as the sum of the impacts related to the amount of chemical needed plus the amount of soil excavated, as shown in Figure 16. SimaPro calculations for all the alternatives are shown in Appendix III.



Products

| Outputs to technosphere: Products and co-products | Amount | Unit | Quantity | Allocation | Waste type | Category | Coı |
|---|---|---|---|---|---|---|---|
| Excavated soil | 1 | kg | Mass | 100 % | not defined | Others_polluted soil | |
| Add | | | | | | | |

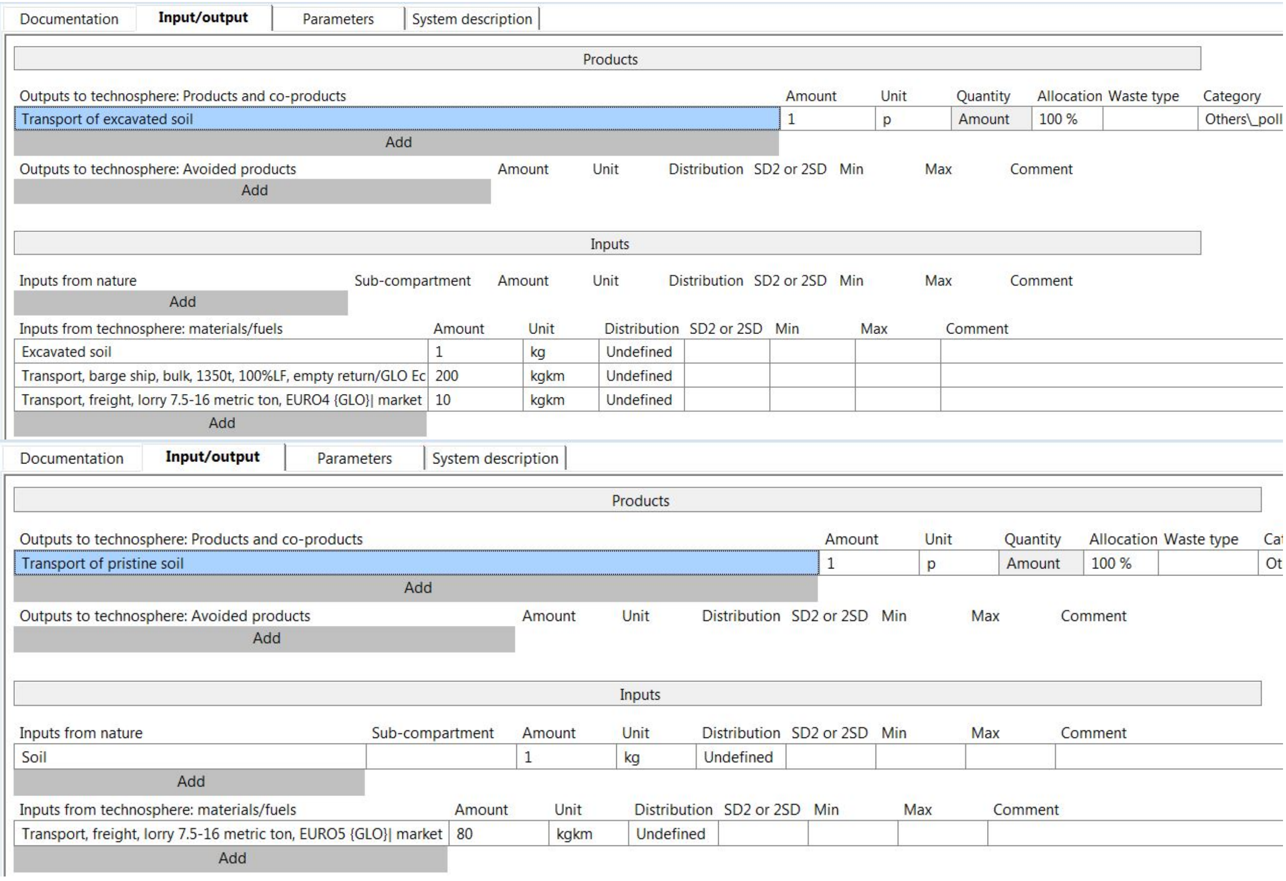
| Outputs to technosphere: Avoided products | Amount | Unit | Distribution | SD2 or 2SD | Min | Max | Comment |
|---|---|---|---|---|---|---|---|
| Add | | | | | | | |

Inputs

| Inputs from nature | Sub-compartment | Amount | Unit | Distribution | SD2 or 2SD | Min | Max | Comment |
|---|---|---|---|---|---|---|---|---|
| Add | | | | | | | | |

| Inputs from technosphere: materials/fuels | Amount | Unit | Distribution | SD2 or 2SD | Min | Max | Comment |
|---|---|---|---|---|---|---|---|
| Excavation, hydraulic digger {GLO}\| market for \| APOS, U | 0,000571 | m3 | Undefined | | | | |
| Excavation, skid-steer loader {GLO}\| market for \| APOS, U | 0,000571 | m3 | Undefined | | | | |
| Add | | | | | | | |

*Figure 14. Modelling of the process of excavation in SimaPro. The data about the inputs from technosphere were taken from* (Suer & Andersson-Sköld, 2011).



Products

| Outputs to technosphere: Products and co-products | Amount | Unit | Quantity | Allocation | Waste type | Category |
|---|---|---|---|---|---|---|
| Transport of excavated soil | 1 | p | Amount | 100 % |  | Others_poll |

| Outputs to technosphere: Avoided products | Amount | Unit | Distribution | SD2 or 2SD | Min | Max | Comment |
|---|---|---|---|---|---|---|---|

Inputs

| Inputs from nature | Sub-compartment | Amount | Unit | Distribution | SD2 or 2SD | Min | Max | Comment |
|---|---|---|---|---|---|---|---|---|

| Inputs from technosphere: materials/fuels | Amount | Unit | Distribution | SD2 or 2SD | Min | Max | Comment |
|---|---|---|---|---|---|---|---|
| Excavated soil | 1 | kg | Undefined |  |  |  |  |
| Transport, barge ship, bulk, 1350t, 100%LF, empty return/GLO Ec | 200 | kgkm | Undefined |  |  |  |  |
| Transport, freight, lorry 7.5-16 metric ton, EURO4 {GLO}\| market | 10 | kgkm | Undefined |  |  |  |  |

Products

| Outputs to technosphere: Products and co-products | Amount | Unit | Quantity | Allocation | Waste type | Ca |
|---|---|---|---|---|---|---|
| Transport of pristine soil | 1 | p | Amount | 100 % |  | Ot |

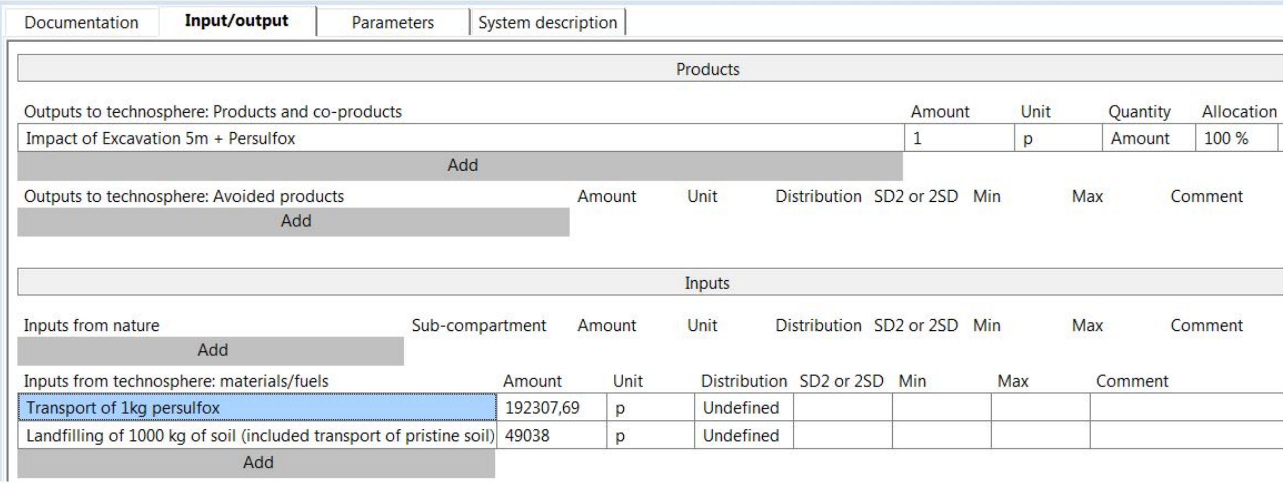
| Outputs to technosphere: Avoided products | Amount | Unit | Distribution | SD2 or 2SD | Min | Max | Comment |
|---|---|---|---|---|---|---|---|

Inputs

| Inputs from nature | Sub-compartment | Amount | Unit | Distribution | SD2 or 2SD | Min | Max | Comment |
|---|---|---|---|---|---|---|---|---|
| Soil |  | 1 | kg | Undefined |  |  |  |  |

| Inputs from technosphere: materials/fuels | Amount | Unit | Distribution | SD2 or 2SD | Min | Max | Comment |
|---|---|---|---|---|---|---|---|
| Transport, freight, lorry 7.5-16 metric ton, EURO5 {GLO}\| market | 80 | kgkm | Undefined |  |  |  |  |

*Figure 15. Modelling of the transport of the landfilling and transport of filling material.*



Products

| Outputs to technosphere: Products and co-products | Amount | Unit | Quantity | Allocation |
|---|---|---|---|---|
| Impact of Excavation 5m + Persulfox | 1 | p | Amount | 100 % |

| Outputs to technosphere: Avoided products | Amount | Unit | Distribution | SD2 or 2SD | Min | Max | Comment |
|---|---|---|---|---|---|---|---|

Inputs

| Inputs from nature | Sub-compartment | Amount | Unit | Distribution | SD2 or 2SD | Min | Max | Comment |
|---|---|---|---|---|---|---|---|---|

| Inputs from technosphere: materials/fuels | Amount | Unit | Distribution | SD2 or 2SD | Min | Max | Comment |
|---|---|---|---|---|---|---|---|
| Transport of 1kg persulfox | 192307,69 | p | Undefined |  |  |  |  |
| Landfilling of 1000 kg of soil (included transport of pristine soil) | 49038 | p | Undefined |  |  |  |  |

*Figure 16. Modelling of the impacts of excavation/landfilling + ISCO. In this example, the excavation and transport of the first 5 meters of soil + the use of PersulfOx on the remaining soil is presented.*

*Impacts during the remedial actions*

The environmental impacts during the remedial activities were linked to the likelihood of having undesired spreading of chemicals and/or contamination due to the remediation itself, the hazard of creating dangerous by-products and other negative environmental effects. Table 13 summarises these features of each alternative, where a score was given in a semi-quantitative way: a score of 0 corresponds to a 'null' effect or risk, a score of 1-2 to a 'low' effect or risk, a score of 3-4 corresponds to a 'medium' effect or risk, a score of 5-6 to a 'high' effect or risk.

*Table 13. Environmental impacts of the remedial alternatives, where Alt.1=5m excavation + ISCO, Alt.2=1m excavation + 4m S/S + ISCO, Alt.3=5m excavation + bioremediation, Alt.4=1m excavation + 4m S/S + bioremediation, Alt.5=ISTS. 0=no impact, 1-2=low impact, 3-4=medium impact, 5-6=high impact.*

| | Alt. 1 | Alt. 2 | Alt. 3 | Alt. 4 | Alt. 5 |
|---|---|---|---|---|---|
| Risk of spreading of chemical or contamination | 1 | 0 | 1 | 0 | 1 |
| Risk of hazardous by-products formation | 1 | 1 | 1 | 1 | 3 |
| Other environmental effects (aquifer acidification, metals mobilization, emissions to air, etc.) | 2 | 2 | 1 | 1 | 1 |

No hazardous by-products are formed from the reaction between PAH and persulfate and the risk of spreading the chemical or the contamination is low for ISCO (Petri, et al., 2010; Tsitonaki, et al., 2010; Liao, et al., 2014; Siegrist, et al., 2014). The risk of spreading becomes even lower when stabilization/solidification is coupled with ISCO. Other environmental effects related to the use of ISCO are linked to the risk of aquifer acidification, temporary effects on biomasses and the potential of mobilize metals, notably $Cr^{3+}$ (Petri, et al., 2010; Tsitonaki, et al., 2010; Liao, et al., 2014; Siegrist, et al., 2014).

The use of the ORC solution for bioremediation has little environmental effects, where the risk of spreading the contamination is associated only with the normal drilling for pipes and boreholes. There is no risk of by-products formation or other environmental hazards observed in most cases (Lu et al., 2017; WDNR, 2012; Juwarkar et al., 2010; Kunucku, 2007), with the exception of a study that points to that it might be possible that oxy-PAH and PAH-ketones might be formed during the microbial metabolism of some PAH (Bamforth & Singleton, 2005).

The risk of spreading the contamination when using ISTS was considered to be low, and due, as for ISCO and bioremediation, to the action of drilling to make the holes for the pipes or heaters. The risk of by-product formation is however higher than for the other alternatives, because it was observed how some lower molecular weight PAH might remain in the soil after thermal treatment as a result of the cracking of higher molecular weights PAH, and that some oxygenated molecules such as furans might be formed as a consequence of the high temperatures (Gan, et al., 2009). Other environmental effects are related to the emissions in the air of PAH and other combustion products, but these problems are usually successfully overcome with the implementation of air treatment systems (Kuppusamy, et al., 2016; 2017).

From the literature mentioned above, these environmental impacts seemed to be similar in the three different matrices (soil, groundwater and surface water) for the studied remediation methods, therefore the scoring was assumed to be the same in the subcriteria of E1 (soil), E3 (groundwater) and E4 (surface water). However, in projects involving different remediation methods it might not be the case.

### 5.4.3. Scoring process of the environmental criteria

In the next sections, the application to the case-study of the scoring processes of the environmental criteria described in Section 3.4 is shown.

*E1 – Soil*

The sub-criterion ‘Ecotoxicological risk SC on-site’ was scored quantifying the reduction of the negative effects of the contamination on soil obtained with the remedial action. Since the concentration of PAH in the soil was much higher than both the international and site-specific guideline values, it was decided to assign a value of 10 to the alternatives that could give a complete remediation.

The sub-criterion ‘Ecotoxicological risk RA on-site’ was scored as described in the methods (Section 3.4). The passages are shown below (Figures 17, 18 and 19). The first passage consisted in creating the structure to be used in Web-HIPRE, as shown in Figure 17.

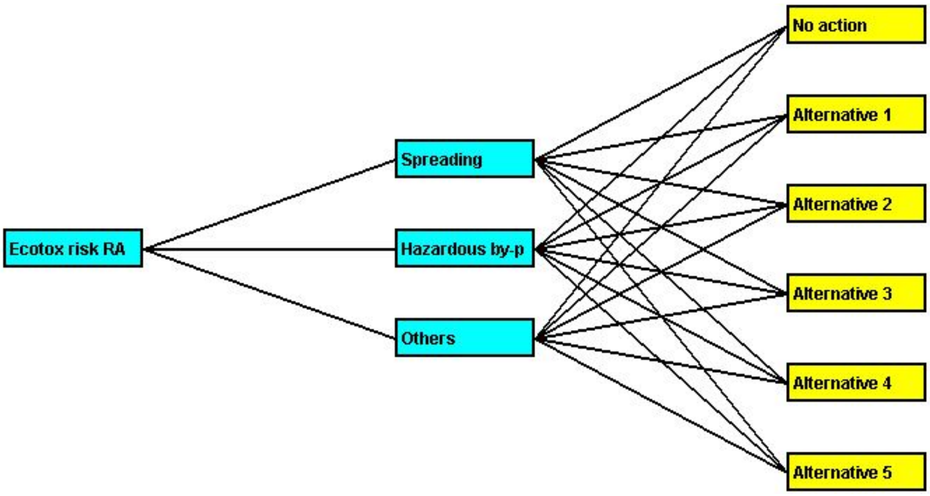
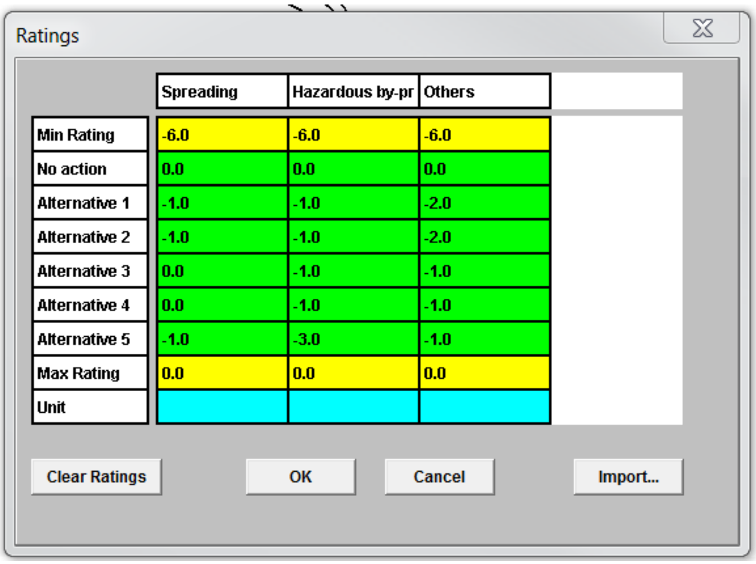


*Figure 17. Structure used in Web-HIPRE to score the sub-criterion ‘Ecotox risk RA on-site’.*

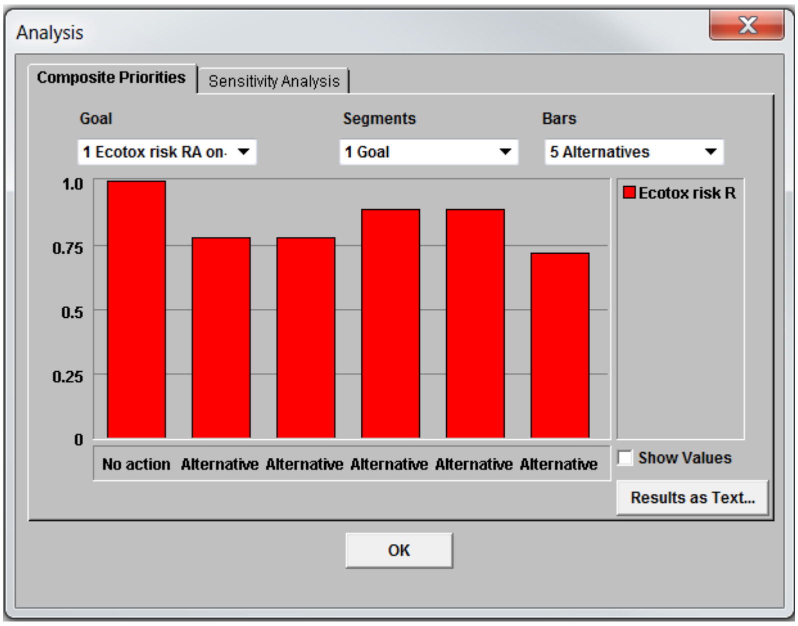
Once the structure was created, the values shown in Table 13 were used as inputs in Web-HIPRE (Figure 18).



| | Spreading | Hazardous by-pr | Others |
|---|---|---|---|
| Min Rating | -6.0 | -6.0 | -6.0 |
| No action | 0.0 | 0.0 | 0.0 |
| Alternative 1 | -1.0 | -1.0 | -2.0 |
| Alternative 2 | -1.0 | -1.0 | -2.0 |
| Alternative 3 | 0.0 | -1.0 | -1.0 |
| Alternative 4 | 0.0 | -1.0 | -1.0 |
| Alternative 5 | -1.0 | -3.0 | -1.0 |
| Max Rating | 0.0 | 0.0 | 0.0 |
| Unit | | | |

*Figure 18. Input values used to score E1 in Web-HIPRE.*

According to the given inputs, the program calculated how the different alternatives scored regarding the sub-criterion ‘Ecotoxicological risk RA on-site’, ranking them with values from 0 to 1, where higher was the input value (thus, higher was the negative effect), lower was score (Figure 19). The sub-subcriteria contributed equally to the scoring (33% of the weight each).



Goal: 1 Ecotox risk RA on-

Segments: 1 Goal

Bars: 5 Alternatives

☐ Show Values

*Figure 19. Outputs from Web-HIPRE analysis.*

The scale used in SCORE for the negative effects of the remedial actions goes from -10 to 0, therefore the outputs from Web-HIPRE were transformed in SCORE scale according to equation 9:

$$SCORE\ input = -10\times(1-(output\ from\ WebHIPRE)) \qquad \text{Eq. 9}$$

The results were then used as input values in SCORE (Table 14).

*Table 14. Input used in SCORE from Web-HIPRE’s results, as shown in equation 9.*

| **Criterion and sub-criterion** | **Alt.1** | **Alt.2** | **Alt.3** | **Alt.4** | **Alt.5** |
|---|---|---|---|---|---|
| E1 – Soil; Ecotoxicological risk RA on-site | -2 | -1 | -1 | -1 | -3 |

The last sub-criterion of E1 is about changes in soil function. It was not considered relevant because the site will be used for residential buildings and offices and soil functions do not play an important role in this case.

*E2 – Flora & fauna*

The effects of the remedial activity on the flora and fauna on-site are usually assessed taking into consideration negative effects on valuable flora and fauna. However, the site is an industrial area without any of the above, so it was not considered important.

*E3 – Groundwater*

Groundwater was assumed to be present only on-site. The sub-criterion ‘Groundwater SC on-site’ was scored by quantifying the reduction of the negative effects from the contamination on the groundwater obtained when the remedial action has been carried out. Since the concentrations of both PAH and benzene in the site were much higher the international and site-specific guidelines, it was decided to assign a value of +10 to the alternatives that could give a complete remediation.

The sub-criterion 'Groundwater RA on-site' was scored as described in Section 3.4, in the same way as presented for the case-study of this project for E1.

*E4 – Surface water*
Surface water is assumed to be present only off-site, and it is sea water. The sub-criterion 'Surface water SC off-site' was scored quantifying the reduction of the negative effects due to the source of contamination gained through the remedial techniques. No site-specific values for PAH in surface water were given, however, the concentration of PAH in surface water should not be detectable (USEPA, 2000), so it was decided to assign a value of 10 to the remediation alternatives that could prevent further spreading of contaminants to the nearby surface water.

The sub-criterion 'Surface water RA off-site' was scored as described in Section 3, in the same way as presented for the case-study of this project for E1.

*E5 – Sediments*
Sediments are only present off-site. However, they are at present heavily contaminated and in need for remediation (Kemakta, 2016). Therefore, it was assumed that the remedial action would not have any effect on the contamination of sediments off-site, neither positive nor negative.

*E6 – Air*
As it has been described previously, the main activities having emissions in the air are the production and transport of the chemicals for ISCO, the energy requirements for ISTD and the emissions during excavation and transport in the case of excavation/landfilling. Quantification of the air emissions during production and transport of the chemicals to the site and for the excavation/landfilling method was done with the SimaPro software. SimaPro gives the results as impacts on different categories, and only the ones relevant for this criterion were used.
Section 3.4 describes the quantitative approach used to score this criterion, and in this section the application of this approach is shown for the case-study. Here, only the scoring of the criteria for scenario I, II and IIIa are shown, but the methodology used was the same for scenario I, II and IIIb. The two transportation scenarios (a and b) considered in SCORE had different inputs and results for this criterion depending on what kind of transport was used to bring the soil to the landfill. Appendix III shows the SimaPro structure for this criterion, and Appendix IV shows the structure used in Web-HIPRE.

The starting point to score this criterion were the outputs from SimaPro. From all the impacts, only the ones relevant to the criterion were chosen, as shown in Table 15.

*Table 15. Selected outputs from SimaPro for E6.*

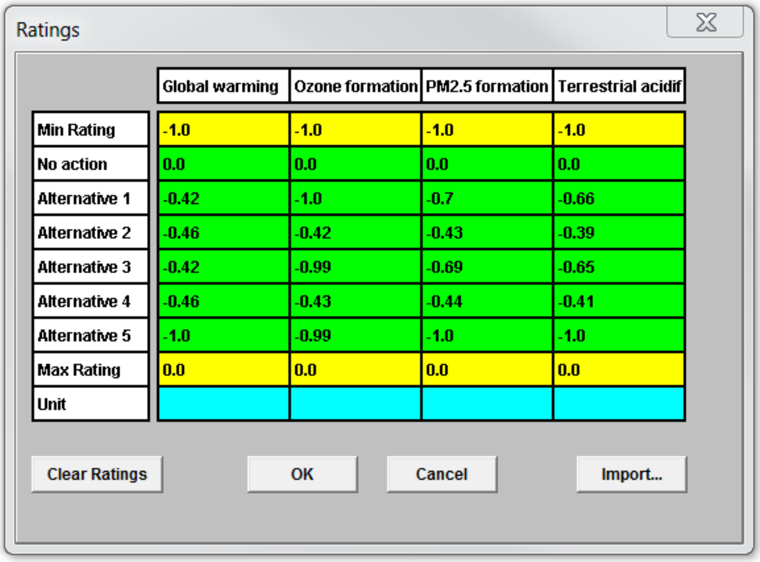
| Impact category | Unit | Alt.1 | Alt.2 | Alt.3 | Alt.4 | Alt.5 |
|---|---|---|---|---|---|---|
| Global warming | kg CO2 eq | 1335623 | 1420237 | 1336305 | 1439632 | 3116444 |
| Ozone formation, Human health | kg NOx eq | 4728.7 | 2881 | 4660.4 | 2920 | 4645 |
| Fine particulate matter formation | kg PM2.5 eq | 1563.1 | 1022.4 | 1546.4 | 1049.6 | 2300 |
| Terrestrial acidification | kg SO2 eq | 3663.5 | 2582.6 | 3617.2 | 2661 | 6083 |

As already described in the methods, these impacts were then normalized dividing each value by the maximum value of each category, which results are shown in Table 16.

*Table 16. Impacts from SimaPro normalized.*

| Impact category | Alt.1 | Alt.2 | Alt.3 | Alt.4 | Alt.5 |
|---|---|---|---|---|---|
| Global warming | 0.43 | 0.46 | 0.43 | 0.46 | 1.00 |
| Ozone formation, Human health | 1.00 | 0.61 | 0.99 | 0.62 | 0.98 |
| Fine particulate matter formation | 0.68 | 0.44 | 0.67 | 0.46 | 1.00 |
| Terrestrial acidification | 0.60 | 0.42 | 0.59 | 0.44 | 1.00 |

These values were then used as inputs in Web-HIPRE, with the same procedure already described above for criteria E1, E3 and E4. Figures 20 and 21 show the inputs and outputs in Web-HIPRE used to score criteria E6 for scenario I, II and III a. The structure used in Web-HIPRE for these criteria is shown in Appendix IV.



| | Global warming | Ozone formation | PM2.5 formation | Terrestrial acidif |
|---|---|---|---|---|
| Min Rating | -1.0 | -1.0 | -1.0 | -1.0 |
| No action | 0.0 | 0.0 | 0.0 | 0.0 |
| Alternative 1 | -0.42 | -1.0 | -0.7 | -0.66 |
| Alternative 2 | -0.46 | -0.42 | -0.43 | -0.39 |
| Alternative 3 | -0.42 | -0.99 | -0.69 | -0.65 |
| Alternative 4 | -0.46 | -0.43 | -0.44 | -0.41 |
| Alternative 5 | -1.0 | -0.99 | -1.0 | -1.0 |
| Max Rating | 0.0 | 0.0 | 0.0 | 0.0 |
| Unit | | | | |

*Figure 20. Input values used to score E6 in Web-HIPRE.*

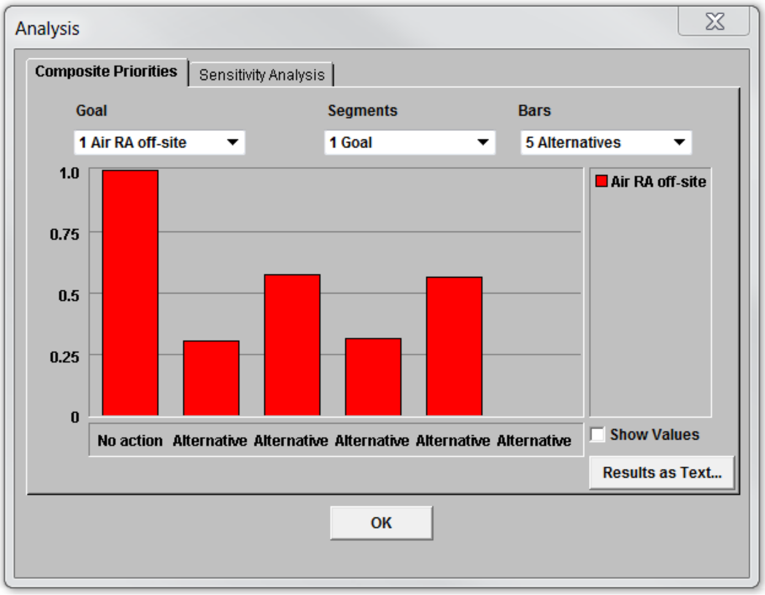

Goal: 1 Air RA off-site
Segments: 1 Goal
Bars: 5 Alternatives

*Figure 21. Results from Web-HIPRE analysis for criterion E6.*

*E7 – Non-renewable natural resources*

As already described in Section 3, SimaPro results regarding fossil resource scarcity and water consumption were used to score this criterion in SCORE, together with the amount of pristine soil needed to fill the excavation, in the same way as described for E6. The two transport scenarios considered in SCORE had different results for this criterion depending on what kind of transport was used for landfilling, and here only scenarios I, II and III a are shown. Appendix III shows the SimaPro structure for this criterion, and Appendix IV shows the structure used in Web-HIPRE. Table 17 shows the outputs of SimaPro chosen as subcriteria to score E7, and Table 18 shows them after the normalization, carried out in the same way as described for E6.

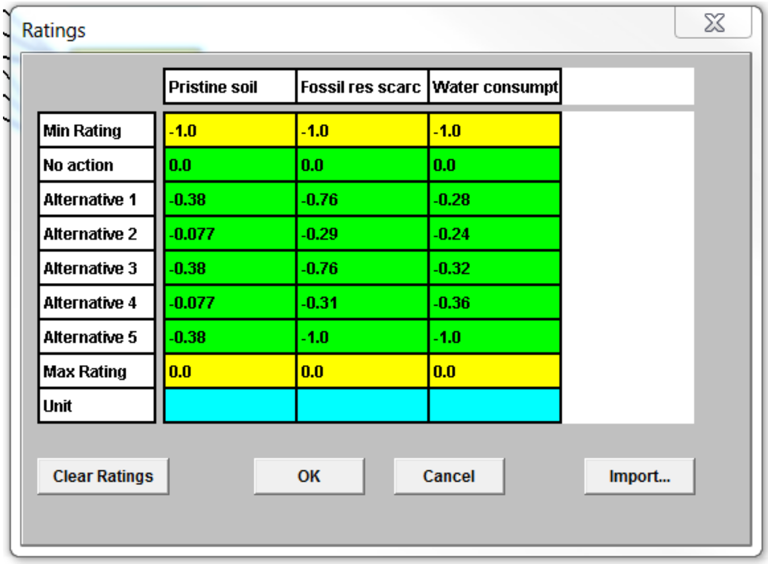
*Table 17. Selected outputs from SimaPro for E7.*

| Impact category | Unit | Alt.1 | Alt.2 | Alt.3 | Alt.4 | Alt.5 |
|---|---|---|---|---|---|---|
| Fossil resource scarcity | kg oil eq | 447122,43 | 211620,62 | 447208,69 | 217765,03 | 652344,7 |
| Water consumption | m3 | 4033,0349 | 4792,8732 | 5046,8723 | 5855,2281 | 19667,13 |

*Table 18. Impacts from SimaPro normalized.*

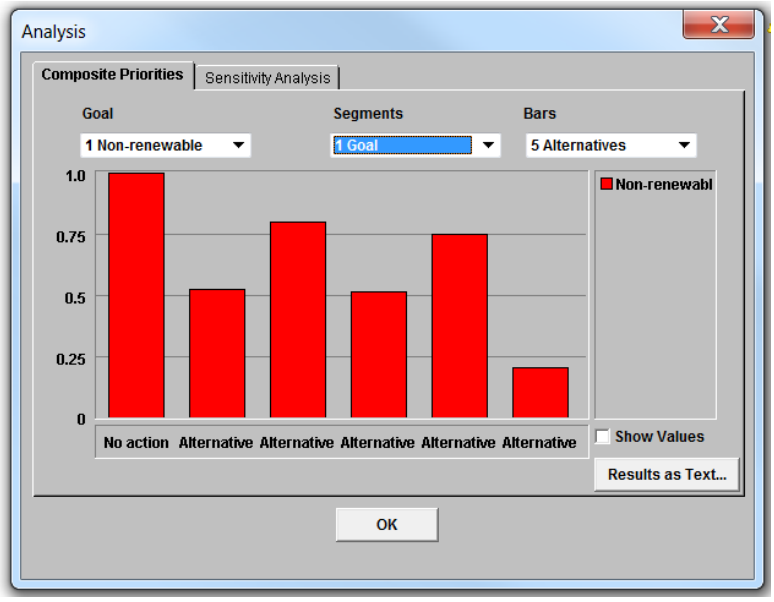
| Impact category | Alt.1 | Alt.2 | Alt.3 | Alt.4 | Alt.5 |
|---|---|---|---|---|---|
| Fossil resource scarcity | 0,69 | 0,32 | 0,69 | 0,33 | 1,00 |
| Water consumption | 0,21 | 0,24 | 0,26 | 0,30 | 1,00 |

Figure 22 and 23 show the inputs and outputs in Web-HIPRE used to score criteria E7 for scenario I, II and IIIa. The structure used in Web-HIPRE for these criteria is shown in Appendix IV. Equation 9 was used to transform the outputs of Web-HIPRE to the same scale used for the inputs in SCORE.



| | Pristine soil | Fossil res scarc | Water consumpt |
|---|---|---|---|
| Min Rating | -1.0 | -1.0 | -1.0 |
| No action | 0.0 | 0.0 | 0.0 |
| Alternative 1 | -0.38 | -0.76 | -0.28 |
| Alternative 2 | -0.077 | -0.29 | -0.24 |
| Alternative 3 | -0.38 | -0.76 | -0.32 |
| Alternative 4 | -0.077 | -0.31 | -0.36 |
| Alternative 5 | -0.38 | -1.0 | -1.0 |
| Max Rating | 0.0 | 0.0 | 0.0 |
| Unit | | | |

*Figure 22. Input values used to score E7 in Web-HIPRE.*



Goal: 1 Non-renewable

Segments: 1 Goal

Bars: 5 Alternatives

*Figure 23. Outputs from Web-HIPRE.*

*E8 – Non-recyclable waste*

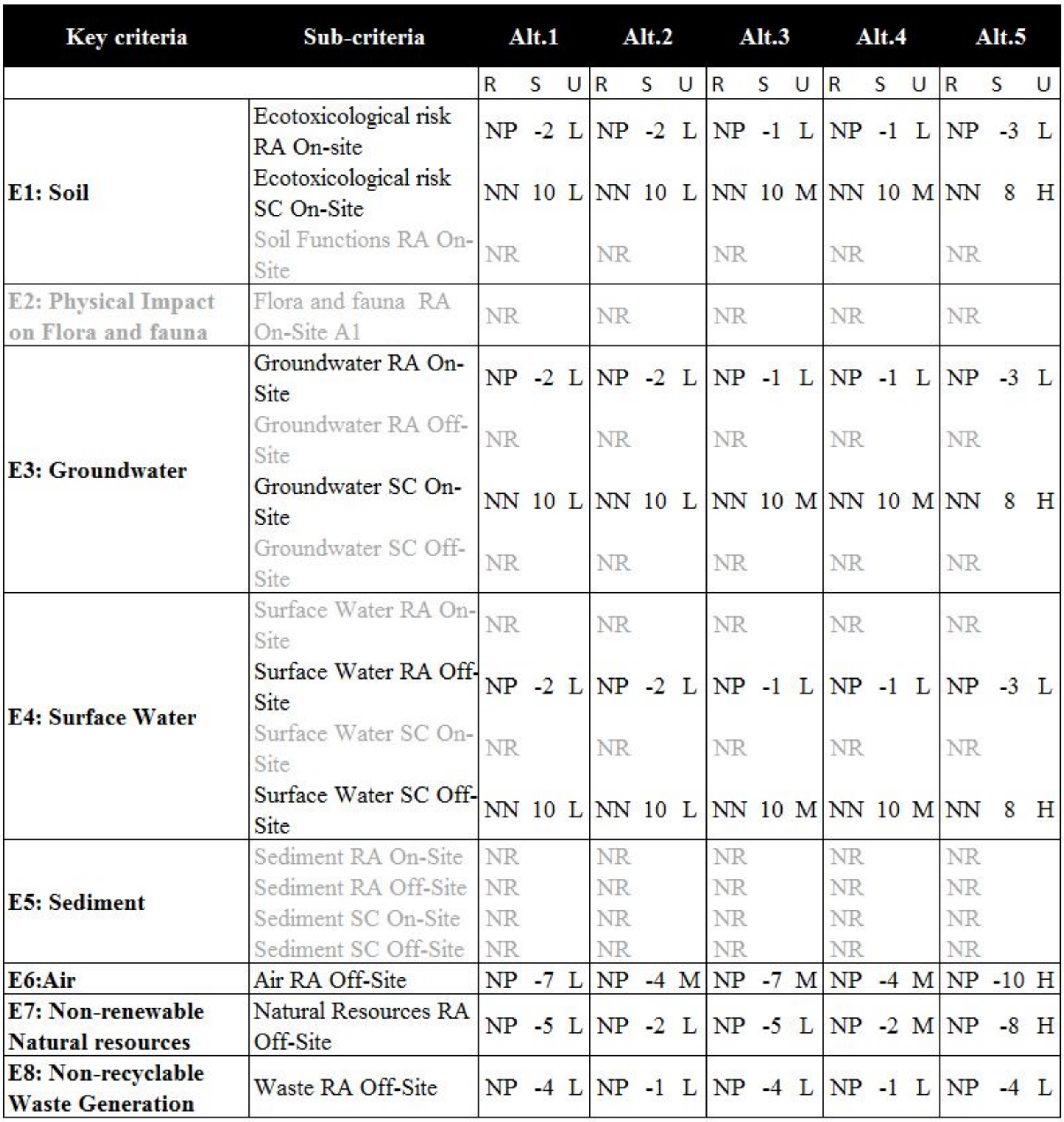
The waste resulting from the RA were considered to be negligible for all the techniques that did not involve excavation, considering the big amount of waste produced by the latter (where the contaminated soil excavated and landfilled is considered as waste). Therefore, for this criterion, the worst scenario, translated as the highest negative score, was considered the eventuality where all the soil was excavated and landfilled, and the criteria for the other techniques could be scored depending on how much soil was landfilled in each RA.

In case of complete excavation and landfill disposal, 75 000 $m^3$ of soil would resulted as a waste, and that would mean a score of -10 in SCORE. In the cases involving excavation of the first 5 meters of soil, the waste resulting would be 28 846 $m^3$ of soil, that in proportion would give a score of -4 (approximated from -3.8) in SCORE. In the case involving the excavation of the first meter of soil, the waste resulting would be 9 808 $m^3$ of soil, resulting in a score of -1 (approximated from -0.8) in SCORE.

### 5.4.4. Scores of the environmental criteria

Table 19 shows the scores assigned to the environmental criteria for transportation scenario a, their range and the uncertainty. Appendix V shows the final scoring for the second transportation scenario (b).

*Table 19. SCORE inputs for the environmental criteria, scenario a. AS=all scores possible, NP=no positive score possible, NN=no negative scores possible, NR=not relevant. Regarding the uncertainty, L=low, M=medium and H=high.*



| Key criteria | Sub-criteria | Alt.1 | | | Alt.2 | | | Alt.3 | | | Alt.4 | | | Alt.5 | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | R | S | U | R | S | U | R | S | U | R | S | U | R | S | U |
| **E1: Soil** | Ecotoxicological risk RA On-site | NP | -2 | L | NP | -2 | L | NP | -1 | L | NP | -1 | L | NP | -3 | L |
| | Ecotoxicological risk SC On-Site | NN | 10 | L | NN | 10 | L | NN | 10 | M | NN | 10 | M | NN | 8 | H |
| | Soil Functions RA On-Site | NR | | | NR | | | NR | | | NR | | | NR | | |
| **E2: Physical Impact on Flora and fauna** | Flora and fauna RA On-Site A1 | NR | | | NR | | | NR | | | NR | | | NR | | |
| **E3: Groundwater** | Groundwater RA On-Site | NP | -2 | L | NP | -2 | L | NP | -1 | L | NP | -1 | L | NP | -3 | L |
| | Groundwater RA Off-Site | NR | | | NR | | | NR | | | NR | | | NR | | |
| | Groundwater SC On-Site | NN | 10 | L | NN | 10 | L | NN | 10 | M | NN | 10 | M | NN | 8 | H |
| | Groundwater SC Off-Site | NR | | | NR | | | NR | | | NR | | | NR | | |
| **E4: Surface Water** | Surface Water RA On-Site | NR | | | NR | | | NR | | | NR | | | NR | | |
| | Surface Water RA Off-Site | NP | -2 | L | NP | -2 | L | NP | -1 | L | NP | -1 | L | NP | -3 | L |
| | Surface Water SC On-Site | NR | | | NR | | | NR | | | NR | | | NR | | |
| | Surface Water SC Off-Site | NN | 10 | L | NN | 10 | L | NN | 10 | M | NN | 10 | M | NN | 8 | H |
| **E5: Sediment** | Sediment RA On-Site | NR | | | NR | | | NR | | | NR | | | NR | | |
| | Sediment RA Off-Site | NR | | | NR | | | NR | | | NR | | | NR | | |
| | Sediment SC On-Site | NR | | | NR | | | NR | | | NR | | | NR | | |
| | Sediment SC Off-Site | NR | | | NR | | | NR | | | NR | | | NR | | |
| **E6:Air** | Air RA Off-Site | NP | -7 | L | NP | -4 | M | NP | -7 | M | NP | -4 | M | NP | -10 | H |
| **E7: Non-renewable Natural resources** | Natural Resources RA Off-Site | NP | -5 | L | NP | -2 | L | NP | -5 | L | NP | -2 | M | NP | -8 | H |
| **E8: Non-recyclable Waste Generation** | Waste RA Off-Site | NP | -4 | L | NP | -1 | L | NP | -4 | L | NP | -1 | L | NP | -4 | L |

## 5.5. Social criteria

### 5.5.1. Selection of the relevant criteria

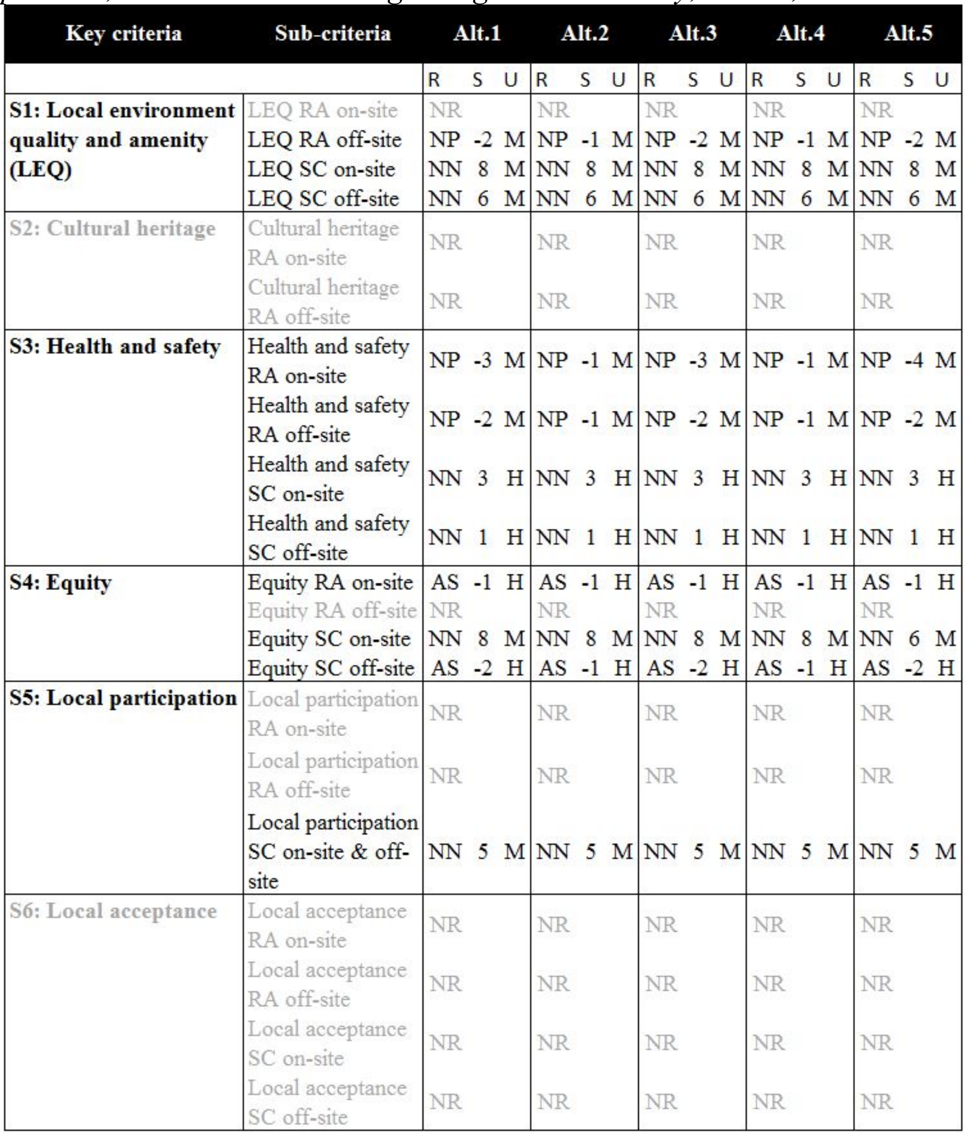
The relevant criteria were selected depending on the specifics of the site. Although the scoring was based on the idealized site and not on the real one, the geolocation and geography of the site and the area around the site were kept as for the real one. Here, the important assumptions regarding the idealized site were that no inhabitants were present on-site and that only old dismissed buildings of no historical value were present on-site. These assumptions were based on observations using Google

Maps (both from satellite and with street view version) and information present on-line. Therefore, the choice of the relevant criteria depended on the features of the real site as well.

### 5.5.2. Scoring of the social criteria

Table 20 shows the scoring for transportation scenario a, whereas the detailed scoring for scenario b is presented in Appendix VI. The next sections provide motivations for the scoring.

*Table 20. SCORE inputs for the social criteria, scenario I, II and III a. R=range, S=score, U=uncertainty AS=all scores possible, NP=no positive score possible, NN=no negative scores possible, NR=not relevant. Regarding the uncertainty, L=low, M=medium and H=high.*



| Key criteria | Sub-criteria | Alt.1 | | | Alt.2 | | | Alt.3 | | | Alt.4 | | | Alt.5 | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | R | S | U | R | S | U | R | S | U | R | S | U | R | S | U |
| **S1: Local environment quality and amenity (LEQ)** | LEQ RA on-site | NR | | | NR | | | NR | | | NR | | | NR | | |
| | LEQ RA off-site | NP | -2 | M | NP | -1 | M | NP | -2 | M | NP | -1 | M | NP | -2 | M |
| | LEQ SC on-site | NN | 8 | M | NN | 8 | M | NN | 8 | M | NN | 8 | M | NN | 8 | M |
| | LEQ SC off-site | NN | 6 | M | NN | 6 | M | NN | 6 | M | NN | 6 | M | NN | 6 | M |
| **S2: Cultural heritage** | Cultural heritage RA on-site | NR | | | NR | | | NR | | | NR | | | NR | | |
| | Cultural heritage RA off-site | NR | | | NR | | | NR | | | NR | | | NR | | |
| **S3: Health and safety** | Health and safety RA on-site | NP | -3 | M | NP | -1 | M | NP | -3 | M | NP | -1 | M | NP | -4 | M |
| | Health and safety RA off-site | NP | -2 | M | NP | -1 | M | NP | -2 | M | NP | -1 | M | NP | -2 | M |
| | Health and safety SC on-site | NN | 3 | H | NN | 3 | H | NN | 3 | H | NN | 3 | H | NN | 3 | H |
| | Health and safety SC off-site | NN | 1 | H | NN | 1 | H | NN | 1 | H | NN | 1 | H | NN | 1 | H |
| **S4: Equity** | Equity RA on-site | AS | -1 | H | AS | -1 | H | AS | -1 | H | AS | -1 | H | AS | -1 | H |
| | Equity RA off-site | NR | | | NR | | | NR | | | NR | | | NR | | |
| | Equity SC on-site | NN | 8 | M | NN | 8 | M | NN | 8 | M | NN | 8 | M | NN | 6 | M |
| | Equity SC off-site | AS | -2 | H | AS | -1 | H | AS | -2 | H | AS | -1 | H | AS | -2 | H |
| **S5: Local participation** | Local participation RA on-site | NR | | | NR | | | NR | | | NR | | | NR | | |
| | Local participation RA off-site | NR | | | NR | | | NR | | | NR | | | NR | | |
| | Local participation SC on-site & off-site | NN | 5 | M | NN | 5 | M | NN | 5 | M | NN | 5 | M | NN | 5 | M |
| **S6: Local acceptance** | Local acceptance RA on-site | NR | | | NR | | | NR | | | NR | | | NR | | |
| | Local acceptance RA off-site | NR | | | NR | | | NR | | | NR | | | NR | | |
| | Local acceptance SC on-site | NR | | | NR | | | NR | | | NR | | | NR | | |
| | Local acceptance SC off-site | NR | | | NR | | | NR | | | NR | | | NR | | |

It was important to keep in mind the geolocation of the site, because Stockholm is a city of almost 1 million inhabitants. Therefore, when considering the effects that the remediation project may have on, for example, increase in traffic, it was kept in mind that in such a big city the traffic is already quite heavy. Also, when considering the positive effects of having new recreational areas with the completion of the project, it was considered that unlike a small community, Stockholm already had different opportunities somewhere else in the city. Hence, the difference between having or not new opportunities also in this part of the city was considered positive to a lower extent than might be present in other cases, such as in small communities.

*Local environment quality and amenity (LEQ)*
At the time when the scoring was performed, the site did not have any particular recreational value, instead the reference alternative already was associated with extensive physical disturbances in the area and for the surrounding area (off-site) due to the work in progress. Therefore, the remedial action was considered to not result in any significant effect compared to the reference alternative.

Some activities however, related to the RA, were considered to increase the overall disturbances and therefore influencing slightly negatively the score, noticeably the increase of traffic-related nuisances caused by the transport of the soil by truck: a more negative score was assigned to the alternatives involving more excavation, and overall to the scenario where all the soil was transported by truck to the landfill. However, it was assessed that due to the vicinity of the site to the highway and due to the fact that the eventual trucks for the transport of soil and machineries would pass by not very densely populated areas before entering the highway or to transport the soil to the harbour, these negative effects to be low.

Regarding the changes in the source of contamination (SC), without the contamination the redevelopment project was finally considered possible to be implemented, giving great positive effects both on-site and off-site.

*Cultural heritage*
This criterion is relevant only with respects to the remedial action on-site and off-site. At the site, only old dismissed industrial buildings were present, therefore it was decided to disregard this criterion. At adjacent sites however, there are several valuable historical buildings, of which some most probably will be preserved.

*Health and safety*
This criterion is relevant on-site and off-site, with respect to both the remedial action and the source of contamination. The parameters kept in mind while scoring this criterion were the effects on human health and safety due to exposure and spreading of the contaminants in the different environmental matrices and due to accidental risks.

On-site, only workers from the construction sector were considered to be present during the remedial action. It was then considered that all the RA that include excavation and landfilling could lead to an increase in workers exposure to the contaminants and in heavy traffic, resulting in increased effects on-site due to exposure to PAH and off-site due to air pollution and risk of traffic accident. Moreover, it was assumed that if the workers wouldn't have worked on this particular site, they would have been employed somewhere else, being subject to the same risk that are usually related to construction sites. However, some of the techniques were associated with specific safety risks, therefore all the alternatives were analysed in order to point out eventual features that may lead to increased risk for the workers' health and safety: ISCO, S/S and bioremediation could have led to increased safety risk due to eventual reactions between the contaminants and the chemicals, but in the pilot tests no problems were observed. ISTS was assessed to have slightly more risks than the other alternative due to the presence of high temperatures.

The change in the contamination (SC), however, was considered to have a minor but positive effect on-site, because no people were considered to live there in the reference alternative but only workers and pedestrians were assumed to be present. It was also assessed to have some positive effects off-site because the neighbours and the people bathing in the sea/canal were considered less likely to be exposed to the contaminants after the remediation (even though the sediments are also in need of remediation, therefore remediating the contamination on-site would give only low positive effects).

*Equity*
This criterion is relevant on and off-site with respect to the RA and SC. It was observed that on-site there are currently some boats at berth in a small port, thus it was assessed that the RA on-site would influence slightly negatively the people who have the boats there, since thay may face some difficulties in reaching the port. No effects were considered to be present off-site due to the RA.

Positive effects were instead associated with the change in the source contamination on-site (SC), because no environmental costs for the future generation were then supposed to be present. Instead, off-site, at the landfill, some low negative effects were assessed to be present due to the change in the contamination, because the contaminated soil landfilled will be, most likely, a problem for the future generations. The score assigned was more negative with the increase in soil landfilled.

*Local participation*
This criterion is usually relevant on and off-site with respect to the RA and SC. It was considered that no effects due to the remedial action were present on-site since no new local jobs were created, being since the workers are expected to come from an area outside the site. Because the workers are present on-site, slightly positive impacts might be associated with the RA off-site, due to their use of local services. However, being a site located in Stockholm it cannot be assumed that the workers will stay only nearby the site to use the services, and also considering the high affluence of people at the metro station of Ropsten and the people already present due to the work in progress in all the area around the site, these sub-criteria were disregarded due to low relevance. As a result of the change in source contamination, the designed project for the area will be implemented, bringing positive effects regarding to local participation both on and off-site, therefore these two sub-criteria were merged into one and scored accordingly.

*Local acceptance*
This criterion is relevant on and off-site with respect to the RA and SC. It is usually scored by means of workshop with representatives of the local area or by using questionnaires to the residents. However, this was not possible to be done at this stage of the real project, therefore this criterion was not included in the analysis.

## 5.6. Economic criterion

The key criterion of the economic part in SCORE is the social profitability, evaluated my means of a CBA. The benefits and the cost relevant for the CBA are shown in Table 21. The time period chosen for the CBA is 50 years.

*Table 21. Benefits and costs relevant for the site and how they were scored.*

| Criterion | Sub-criteria | How it is scored |
|---|---|---|
| Social profitability | **Benefits** | |
| | Increase property value on-site | Data provided by Stockholm municipality |
| | Improved health | Qualitative evaluation |
| | Increased provision of ecosystem services | Qualitative evaluation |
| | Others | |
| | **Costs** | |
| | Remediation costs | Data collected from different sources and literature |
| | Impaired health due to remedial action | SimaPro results + literature data |
| | Decreased provision of ecosystem services due to remedial action | Qualitative evaluation |

| | | |
|---|---|---|
| | Others | |

### 5.6.1. Benefits

Due to data limitations and time constraints, it was not possible to monetize all the benefits of the remediation. However, a qualitative assessment of all the different benefits was carried out and shown in Table 22, where also the distribution of benefits between the developer, the employees and the public is assessed. Only the benefits that were monetized are further described in the next sections.

*Table 22. Qualitative assessment of the benefits. X=Important, (X)=somewhat important and NR=not relevant.*

| **Benefits: qualitative assessment** | | | | | | |
|---|---|---|---|---|---|---|
| | | **Alt.1** | **Alt.2** | **Alt.3** | **Alt.4** | **Alt.5** |
| **B1. Increased property value on-site** | | | | | | |
| **B1. Increased property value on-site** | Importance | X | X | X | X | X |
| | Time period (months) | 9-12 | 9-12 | 24-36 | 24-36 | 6-9 |
| | *The increased property value in the area due to the remediation is the same for all the alternatives. Depending on the time period, the property value will be realised at different time for the alternatives. The beneficiary of this benefit will be the developer.* | | | | | |
| **B2. Improved health** | | | | | | |
| **B2a. Reduced acute health risks** | Importance | (X) | (X) | (X) | (X) | (X) |
| | Time period (years) | > 50 | > 50 | > 50 | > 50 | > 50 |
| | *The acute human health risks are low in the reference option, so the reduction of these risks is not of primary importance. The beneficiary of this benefit will be the public.* | | | | | |
| **B2b. Reduced non-acute health risks** | Importance | (X) | (X) | (X) | (X) | (X) |
| | Time period (years) | > 50 | > 50 | > 50 | > 50 | > 50 |
| | *All the options are assumed to reach the clean-up goal, meaning that the non-acute health risks are reduced to acceptable levels in all the alternatives. Before the remediation the guidelines values for health protection were exceeded in all the areas of the site, meaning that remediation will provide a significant reduction in health risks. However, before the remediation not many people were present on-site for periods of time long enough to experience non-acute health effects, therefore the importance of this benefit was assessed to be 'somewhat important'. The beneficiary of this benefit will be the public.* | | | | | |
| **B2c. Other types of improved health** | Importance | NR | NR | NR | NR | NR |
| | Time period (years) | 9-12 | 9-12 | 24-36 | 24-36 | 6-9 |
| | *This is primarily about how people's concern about the contamination is affected. No people are present on-site, and it is very likely that the people living off-site are not aware of the contamination in the soil. Therefore, it can be assumed that the remediation would be irrelevant for e.g. decreased anxiety.* | | | | | |
| **B3. Increased provision of ecosystem services** | | | | | | |
| **B3a. Increased recreational opportunities on-site** | Importance | X | X | X | X | X |
| | Time period (years) | >50 | >50 | >50 | >50 | >50 |
| | *All the alternatives will make possible to implement the redevelopment project, which will increase the recreational opportunities on-site (parks, swimming pools and sport centres according to the project). The beneficiary of this benefit will be the public.* | | | | | |
| **B3b. Increased** | Importance | (X) | (X) | (X) | (X) | (X) |
| | Time period (years) | >50 | >50 | >50 | >50 | >50 |

| | | | | | | |
|---|---|---|---|---|---|---|
| **recreational opportunities in the surroundings** | *All the alternatives will make possible to implement the redevelopment project, which will increase the recreational opportunities also in the surroundings. However, being Stockholm a big city with many opportunities for recreational activities, the increase due to this project is not as important as for the site itself. The beneficiary of this benefit will be the public.* | | | | | |
| **B3b. Increased provision of other ecosystem services** | Importance | (X) | (X) | (X) | (X) | (X) |
| | Time period (years) | >50 | >50 | >50 | >50 | >50 |
| | *Reduced leakage from the area after the remediation can affect the pollutants content in the Baltic Sea and in the coastal area of Stockholm, thereby improving the recreational possibilities there. However, these effects are very difficult to detect and there are many other sources of contaminants that contribute to pollution outside the area. The beneficiary of this benefit will be the public.* | | | | | |
| **B4. Other positive externalities than B2 and B3** | Importance | NR | NR | NR | NR | NR |
| | Time period (years) | >50 | >50 | >50 | >50 | >50 |
| | *There are not any other positive externalities that can be influenced by the remediation on-site and off-site that are relevant enough to be taken into account.* | | | | | |

*B1 – Increased property value on-site*

The aim of remediating the Kolkajen site was to redevelop it according to the Norra Djurgårdsstaden project. Therefore, the possibility to build houses, offices, schools and parks was the main driver in the increase land value. According to (unofficial) information from Stockholm municipality's department 'Exploateringskontoret - Avdelningen för Mark och värdering', the value of the site was expected to increase by 3 850 SEK per $m^2$ of available housing area. Therefore, it was assumed that right after the completion of the remediation, the value of the area already present would have increased the abovementioned value. Table 23 shows the expected benefits in increased land value.

*Table 23. Benefits due to increase in land value.*

| | **Benefits (MSEK)** | |
|---|---|---|
| After remediation | 22.2 | (3850 SEK/$m^2$ * 5770 $m^2$) |

*The values shown in the table are not yet discounted.

### 5.6.2. Costs

Due to data limitations and time constraints, it was not possible to monetize all the externalities of the different remediation alternatives. However, a qualitative assessment of all the different costs was carried out and shown in Table 24, where also the distribution of costs between the developer, the employees and the public is assessed. Only the direct costs and externalities that were possible to monetize are presented in the next sections.

*Table 24. Qualitative assessment of the costs. X=Important, (X)=somewhat important and NR=not relevant.*

| **Costs: qualitative assessment** | | | | | | |
|---|---|---|---|---|---|---|
| | | **Alt.1** | **Alt.2** | **Alt.3** | **Alt.4** | **Alt.5** |
| **C1. Remediation costs** | | | | | | |
| **C1. Remediation costs** | Importance | X | X | X | X | X |
| | Time period (months) | 9-12 | 9-12 | 24-36 | 24-36 | 6-9 |
| | *All the costs are shown in Table 25 for all the alternatives. However, uncertainties are high for alt.5 and medium for alt.3 and 4. The payer of these costs is the developer.* | | | | | |
| **C2. Impaired health due to remedial action** | | | | | | |
| | Importance | (X) | (X) | (X) | (X) | (X) |

| | | | | | | |
|---|---|---|---|---|---|---|
| **C2a. Increased health risk on-site** | Time period (years) | 9-12 | 9-12 | 24-36 | 24-36 | 6-9 |
| | *This sub-criterion is mostly related to the workers exposure to contaminants (mostly PAH and benzene) on-site during the remediation works. The risk increases with the amount of soil excavated. However, due to the relatively low exposure time, the risk was assessed to be not so important. Mostly the workers will be subject to these externalities.* | | | | | |
| **C2b. Increased health risks from transport activities** | Importance | X | X | X | X | X |
| | Time period (years) | 9-12 | 9-12 | 24-36 | 24-36 | 6-9 |
| | *This criterion is about accidents during transport and is expected to be correlated with the number of truck loads and mileage. The same applies to road safety risks. Also, health risks due to air emissions during the transport are considered. However, due to the presence already of trucks and machineries for the works going on in the sites nearby, and due to the fact that the trucks will mostly be present on the highway, this sub-criterion was assessed to be dependent only on the air emissions. The public will be subject to these externalities.* | | | | | |
| **C2c. Increased health risk at disposal site** | Importance | (X) | (X) | (X) | (X) | (X) |
| | Time period (years) | 9-12 | 9-12 | 24-36 | 24-36 | 6-9 |
| | *The size of this effect was expected to be correlated with the amount of soil disposed. It can be assumed that the contaminated masses are safely handled at the landfills, therefore this risk was assessed to be less important. The employees at the disposal site will be subject to these externalities.* | | | | | |
| **C2d. Other types of impaired health** | Importance | NR | NR | NR | NR | NR |
| | Time period (years) | | | | | |
| | *This is primarily about how people's concern about the contamination is affected. No people are living on-site, and it is very likely that the people living off-site are not aware of the contamination in the soil. Moreover, due to the already ongoing construction works, people will not be able to distinguish if the trucks and machineries are present to treat the contamination or to do some other kind of works, therefore it can be assumed that their awareness of the contamination risk would not increase due to the remedial activities.* | | | | | |
| **C3. Decreased provision of ecosystem services due to remedial action** | | | | | | |
| **C3a. Decreased provision of ecosystem services on-site** | Importance | NR | NR | NR | NR | NR |
| | Time period (years) | | | | | |
| | *Ecosystem services on-site were already low before the remedial actions due to the nature of the site (ex-industrial site).* | | | | | |
| **C3b. Decreased provision of ecosystem services in the surroundings** | Importance | NR | NR | NR | NR | NR |
| | Time period (years) | | | | | |
| | *There are not present any relevant ecosystems services in the surroundings of the site at the present time. Moreover, they would not be affected by the remedial actions much more than by the works already going-on nearby the site.* | | | | | |
| **C3c. Decreased provision of ecosystem services at disposal site** | Importance | (X) | (X) | (X) | (X) | (X) |
| | Time period (years) | 9-12 | 9-12 | 24-36 | 24-36 | 6-9 |
| | *The magnitude of this effect is assumed to be correlated with the volume of contaminated soil deposited. The pollutants are expected to be handled safely at the landfill, while the land consumption at the landfill will increase with increasing amount of disposed soil. These externalities will affect the public.* | | | | | |
| | Importance | NR | NR | NR | NR | NR |

| | | | | | | |
|---|---|---|---|---|---|---|
| **C4. Other negative externalities than C2 and C3** | Time period (years) | | | | | |
| | *The fact that the old buildings present on-site will disappear is for some extent a negative externality, but due to their low value, it can be disregarded.* | | | | | |

*C1 – Remediation costs*

The remediation costs were investigated for each alternative: design of remedial actions, project management, capital costs, remedial action, monitoring and project risks. They were obtained either from the report by Kemakta, (2016), from information received by experts working on the project (eventual information referring to pilot tests or regarding smaller quantities were scaled up to the amount needed for the site) and from literature. Table 25 shows all the costs considered for the different RA.

*Table 25. Actions included for the different RA and their prices. Literature used for ISTS is Stegemeier & Vinegar, 2000; Lemming, et al., 2013; Kuppusamy, et al., 2017.*

| Action | Unit | Price (average) | Source |
|---|---|---|---|
| Excavation and sorting | SEK/m3 | 100 | Kemakta (2016) |
| Environmental inspection (sampling, 2 persons) | SEK/month | 250000 | Kemakta (2016) |
| Environmental control (chemical analysis) | SEK/piece | 600 | Kemakta (2016) |
| Sheet piling | SEK/m2 | 3000 | Kemakta (2016) |
| Setting of storage areas and water treatment area | 1 piece | 300000 | Kemakta (2016) |
| Water purification including pumping and 'lowering' of GW | SEK/m3 | 100 | Kemakta (2016) |
| Transport of contaminated soil (boat+truck) | SEK/ton | 86,7 | Ecoloop |
| Transport of contaminated soil (truck) | SEK/ton | 111 | Ecoloop |
| Landfilling of non-hazardous soil | SEK/ton | 190 | Kemakta (2016) |
| Landfilling of hazardous soil | SEK/ton | 300 | Kemakta (2016) |
| Landfilling of hazardous soil (including tar in free PAHe) | SEK/ton | 770 | Kemakta (2016) |
| Pristine soil (including transport and refill) | SEK/ton | 100 | Kemakta (2016) |
| ISCO (persulfate) | SEK/m3 | 762 | Project manager |
| S/S (lime/cement) | SEK/m3 | 350 | Project manager + experts |
| S/S (mobilization + FKPS testing) | SEK | 225000 | Project manager |
| Cheap persulfate for S/S, price for the chemical | SEK/ton soil | 1200 | Calculations |
| Cheap persulfate for S/S | SEK/m3 | 705,9 | Project manager + calculations |
| Bioremediation (with ORC solution) | SEK/ton | 566 | |
| ISTS | SEK/ton | 1176.5 | Literature |
| Other costs (design, builder etc.) | | +10% | Kemakta (2016) |
| Unforeseen | | +15% | Kemakta (2016) |

The total price for each alternative is shown in Table 26, while the calculations are shown in Appendix VII. The uncertainties of the cost of each alternative depend on the uncertainties related to the alternatives themselves, as already described (uncertainties in amount of chemicals used, energy requirements, etc.).

*Table 26. Total cost for each RA.*

| | Alternative 1 | Alternative 2 | Alternative 3 | Alternative 4 | Alternative 5 |
|---|---|---|---|---|---|
| Scenario a (MSEK) | 126.64 | 158.66 | 138.46 | 176.33 | 198.05 |
| Scenario b (MSEK) | 127.83 | 158.90 | 139.66 | 176.57 | 199.24 |

*C2 – Impaired health due to remediation actions*
Impaired health due to remediation action was quantified using international standard values regarding cost of $CO_2$, $SO_2$ and $NO_x$ emissions. These values where already available for each remediation alternative from SimaPro results (Appendix III) and the price for emissions of the chemicals were available from European Environmental Agency's reports (EEA, 2014) . Table 27 shows the values and Appendix VII shows the calculations.

*Table 27. Cost of impaired health due to remedial actions.*

| | **Alt.1** | **Alt.2** | **Alt.3** | **Alt.4** | **Alt.5** |
|---|---|---|---|---|---|
| Scenario a (MSEK) | 0.018 | 0.011 | 0.018 | 0.011 | 0.027 |
| Scenario b (MSEK) | 0.013 | 0.010 | 0.013 | 0.010 | 0.022 |

### 5.6.3. Net present values (NPV)

A CBA was performed for each alternative according to equation 4, already shown in Section 3. The total timespan considered for the calculation of the NPV was 50 years, and the discount rate used was 3.5%, common for infrastructure project in Sweden (Nordlöf, 2014). Table 28 shows the results of the CBA as NPV for all the alternatives. Appendix VII shows the details of the calculations.

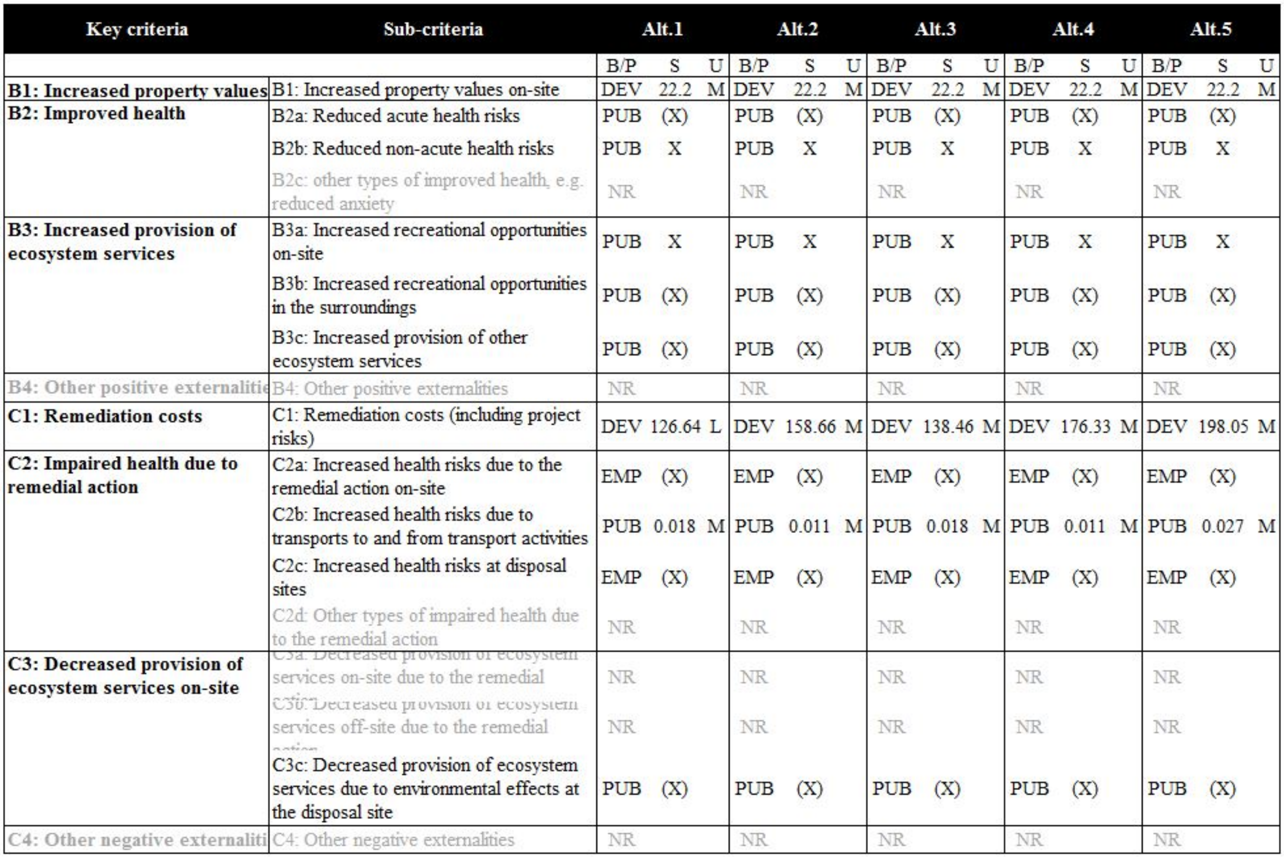
*Table 28. Net present values for the 5 different remediation alternatives.*

| | **Alt.1** | **Alt.2** | **Alt.3** | **Alt.4** | **Alt.5** |
|---|---|---|---|---|---|
| Scenario a (MSEK) | -101 | -132 | -113 | -149 | -170 |
| Scenario b (MSEK) | -102 | -132 | -114 | -150 | -171 |

### 5.6.4. Inputs values for the economic criterion

Table 29 shows the input values in SCORE for the scenario with truck and boat transport (scenario a). The input values for the scenario with only truck transport (scenario b) is shown in Appendix VII. The table shows the distribution of costs and benefits between the payer, the developer, the employees and the public, as described in Table 23 and Table 24.

*Table 29. Input values in SCORE for the economic criterion. P=payer, B=beneficiary, DEV=developer, EMP=employees, PUB=public, NR=not relevant, (X)=non-monetized item judged to be somewhat important, X=non monetized item judged to be very important, S=score, U=uncertainty, L=low uncertainty, M=medium and H=high.*



| Key criteria | Sub-criteria | Alt.1 | | | Alt.2 | | | Alt.3 | | | Alt.4 | | | Alt.5 | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | B/P | S | U | B/P | S | U | B/P | S | U | B/P | S | U | B/P | S | U |
| **B1: Increased property values** | B1: Increased property values on-site | DEV | 22.2 | M | DEV | 22.2 | M | DEV | 22.2 | M | DEV | 22.2 | M | DEV | 22.2 | M |
| **B2: Improved health** | B2a: Reduced acute health risks | PUB | (X) | | PUB | (X) | | PUB | (X) | | PUB | (X) | | PUB | (X) | |
| | B2b: Reduced non-acute health risks | PUB | X | | PUB | X | | PUB | X | | PUB | X | | PUB | X | |
| | B2c: other types of improved health, e.g. reduced anxiety | NR | | | NR | | | NR | | | NR | | | NR | | |
| **B3: Increased provision of ecosystem services** | B3a: Increased recreational opportunities on-site | PUB | X | | PUB | X | | PUB | X | | PUB | X | | PUB | X | |
| | B3b: Increased recreational opportunities in the surroundings | PUB | (X) | | PUB | (X) | | PUB | (X) | | PUB | (X) | | PUB | (X) | |
| | B3c: Increased provision of other ecosystem services | PUB | (X) | | PUB | (X) | | PUB | (X) | | PUB | (X) | | PUB | (X) | |
| **B4: Other positive externaliti** | B4: Other positive externalities | NR | | | NR | | | NR | | | NR | | | NR | | |
| **C1: Remediation costs** | C1: Remediation costs (including project risks) | DEV | 126.64 | L | DEV | 158.66 | M | DEV | 138.46 | M | DEV | 176.33 | M | DEV | 198.05 | M |
| **C2: Impaired health due to remedial action** | C2a: Increased health risks due to the remedial action on-site | EMP | (X) | | EMP | (X) | | EMP | (X) | | EMP | (X) | | EMP | (X) | |
| | C2b: Increased health risks due to transports to and from transport activities | PUB | 0.018 | M | PUB | 0.011 | M | PUB | 0.018 | M | PUB | 0.011 | M | PUB | 0.027 | M |
| | C2c: Increased health risks at disposal sites | EMP | (X) | | EMP | (X) | | EMP | (X) | | EMP | (X) | | EMP | (X) | |
| | C2d: Other types of impaired health due to the remedial action | NR | | | NR | | | NR | | | NR | | | NR | | |
| **C3: Decreased provision of ecosystem services on-site** | C3a: Decreased provision of ecosystem services on-site due to the remedial | NR | | | NR | | | NR | | | NR | | | NR | | |
| | C3b: Decreased provision of ecosystem services off-site due to the remedial | NR | | | NR | | | NR | | | NR | | | NR | | |
| | C3c: Decreased provision of ecosystem services due to environmental effects at the disposal site | PUB | (X) | | PUB | (X) | | PUB | (X) | | PUB | (X) | | PUB | (X) | |
| **C4: Other negative externaliti** | C4: Other negative externalities | NR | | | NR | | | NR | | | NR | | | NR | | |

## 5.7. Scenarios analysed with the SCORE method

In SCORE, it is possible to give different weights to the sustainability domains, the key criteria and the sub-criteria, having hence the possibility to analyse how the assessment changes with different scenarios. Figure 24 shows the weights that were assigned to the three sustainability domains in three different main scenarios analysed in this project: scenarios I, II and III.

It is common that all domains are weighted equally in sustainability assessments (scenario I), however, depending on the user's view of sustainability, or depending on features of the project, the domains can have different weight. It was chosen to test how an increase in the environmental domain's weight would affect the results, assigning 50% of the weight to it, and dividing equally the remaining importance between social and economic domains (scenario II). It was also tested a third scenario to investigate what would be the results if the economic and the environmental domains would be considered more important than the social domain, with the economy of the project being the most important aspect (50% of the weight), followed by the environmental aspect (33%) and lastly the social aspect (17%) (scenario III). All the main scenarios were assessed in respect to the two different transport scenarios (a and b) described in Section 5.3 and Appendix II.

A number of scenarios with different characteristics than the main scenarios were used to investigate how the results would change depending on different features in the setup of the SCORE model. The scenarios analysed are shown in Appendix X, and the reasons why they were analysed are discussed in Section 7. They are:

- Scenario Ia with different weighting given to the environmental criteria and sub-criteria (Scenario x, weighting shown in Appendix XIII).
- Scenario Ia with ‘low’ uncertainties assigned to the economic criteria (Scenario y).
- Scenario Ia with ‘high’ uncertainties assigned to the cost of alternatives 3, 4 and 5 (Scenario z).
- Analysis of alt. 2a, 4a, 2b and 4b (Scenario ‘boat vs truck transport’).

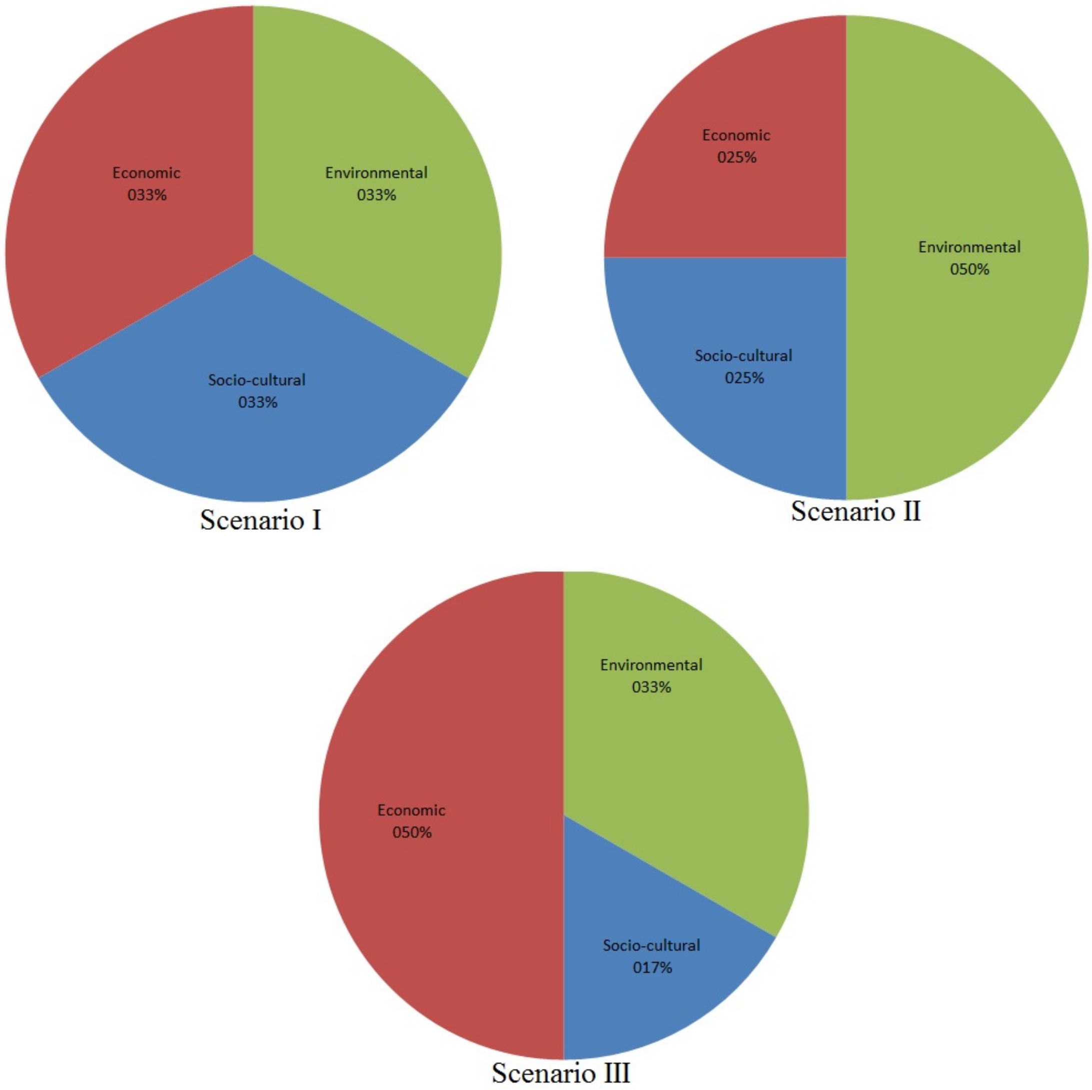


*Figure 24. Weighting of the domains in the different scenarios. From the left to the right are shown scenario I, II and III.*

Figure 25 shows the relative weight given to each criterion in the environmental and social domains in the main scenarios.

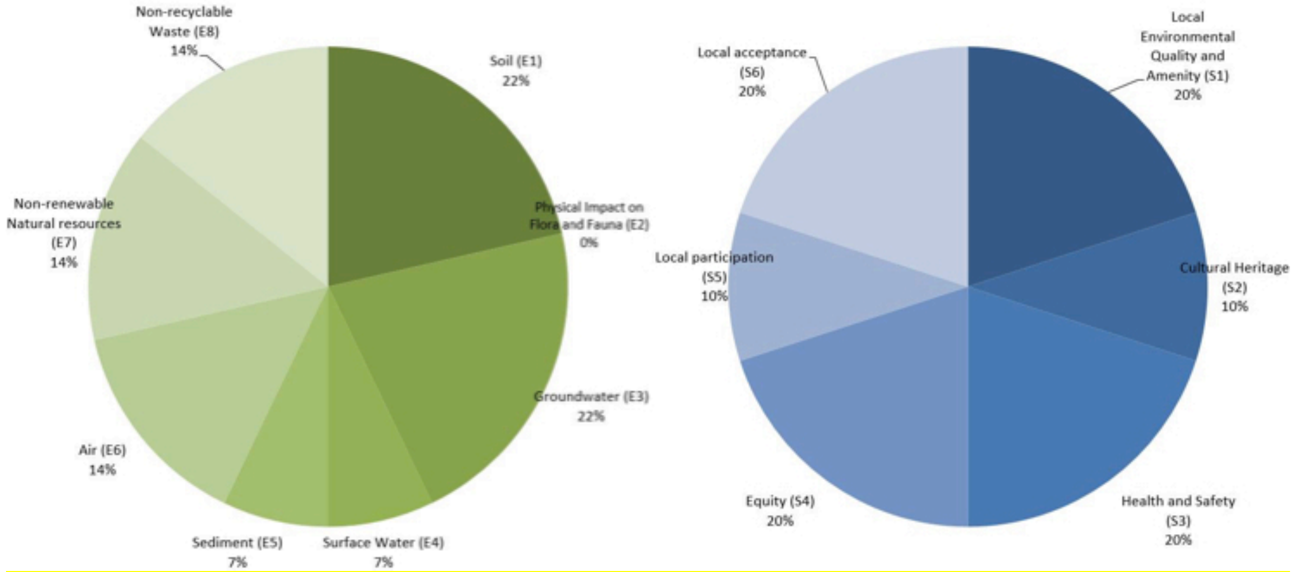


*Figure 25. Weighting of the sub-criteria in the environmental and social criteria. This weighting was kept constant for all the main scenarios.*

# 6. Results

In the following sections, the results from SCORE model are shown for different scenarios:

- Scenario I: all the domains have the same weight; Ia: transport by truck + boat, Ib: transport only by truck.
- Scenario II: environmental domain has 50% of the weight, social and economic have 25% each; IIa: transport by truck + boat; IIb: transport only by truck.
- Scenario III: economic domain has 50% of the weight, followed by environmental (33%) and economic (17%) domains; IIIa: transport by truck + boat; IIIb: transport only by truck.
- Other scenarios, as described in Section 5.7.

## 6.1. Scenario I

Figure 26 shows the environmental, social, economic and total normalized sustainability scores for scenario Ia. Alternative 2 (1m excavation + S/S + ISCO) and 4 (1m excavation + S/S + bioremediation) are the ones that receive the highest total score in the analysis, with a slightly higher score for alternative 2, followed by alternative 1 (5m excavation + ISCO), alternative 3 (5m excavation + bioremediation) and alternative 5 (5m excavation + ISTS), the latter being the only one having a negative total score. It is noticeable that also the difference in score between alternative 1 and 3 is very small. The two alternatives that scored the best in the environmental domain are the ones that also involve the lowest amount of soil to be excavated and landfilled, while alternatives 1 and 3, involving extensive excavation, have a low positive score, with a negative score only for alternative 5, which involves both extensive excavation and high energy use in the thermal treatment. All five alternatives scored quite well in the social domain, with the two alternatives that had the lowest amount of excavated soil scoring better than the others. The economic sustainability shows what was already presented in Table 28: alternative 1 had the highest NPV, followed by alternative 3, 2, 4 and 5.

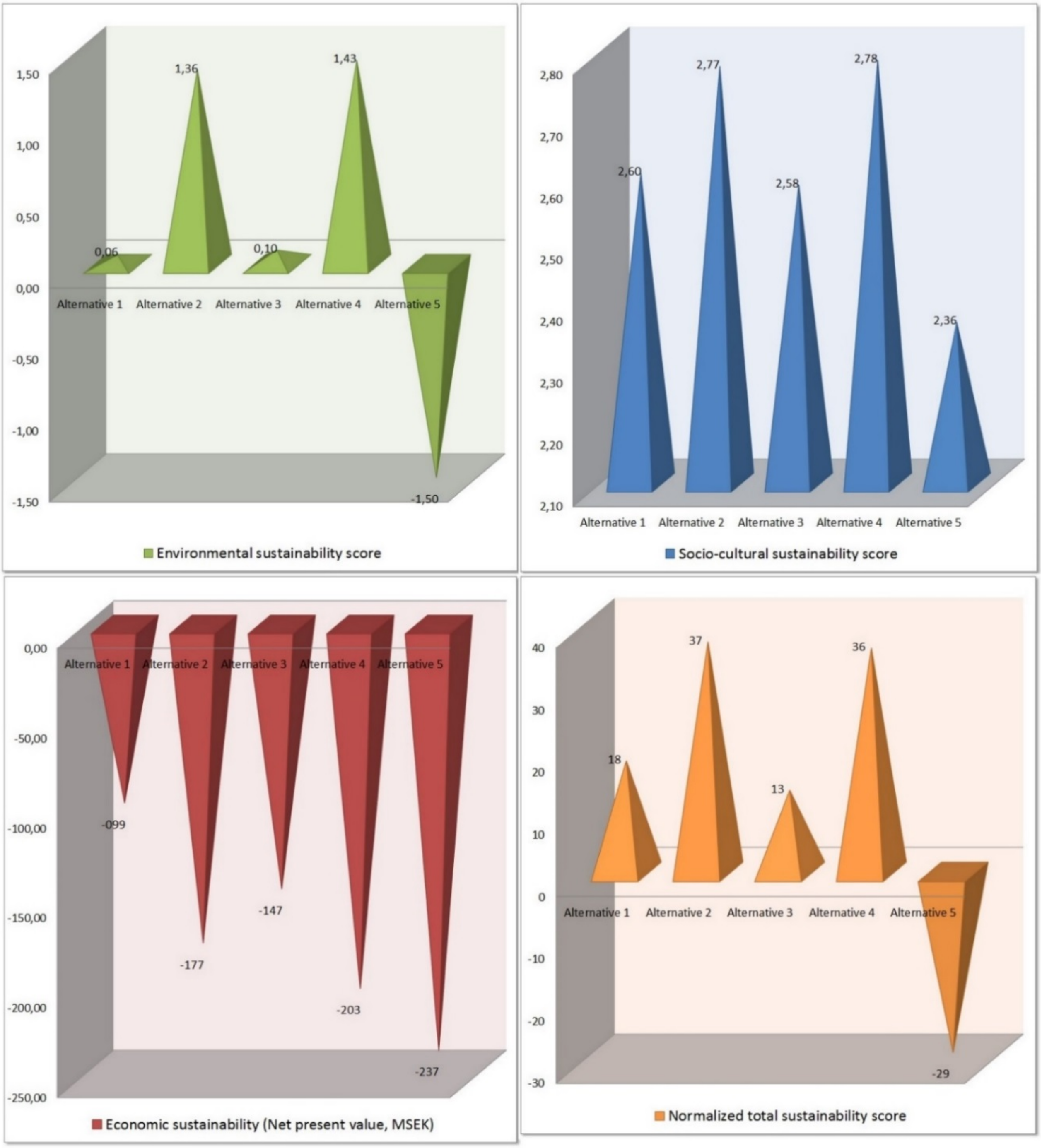
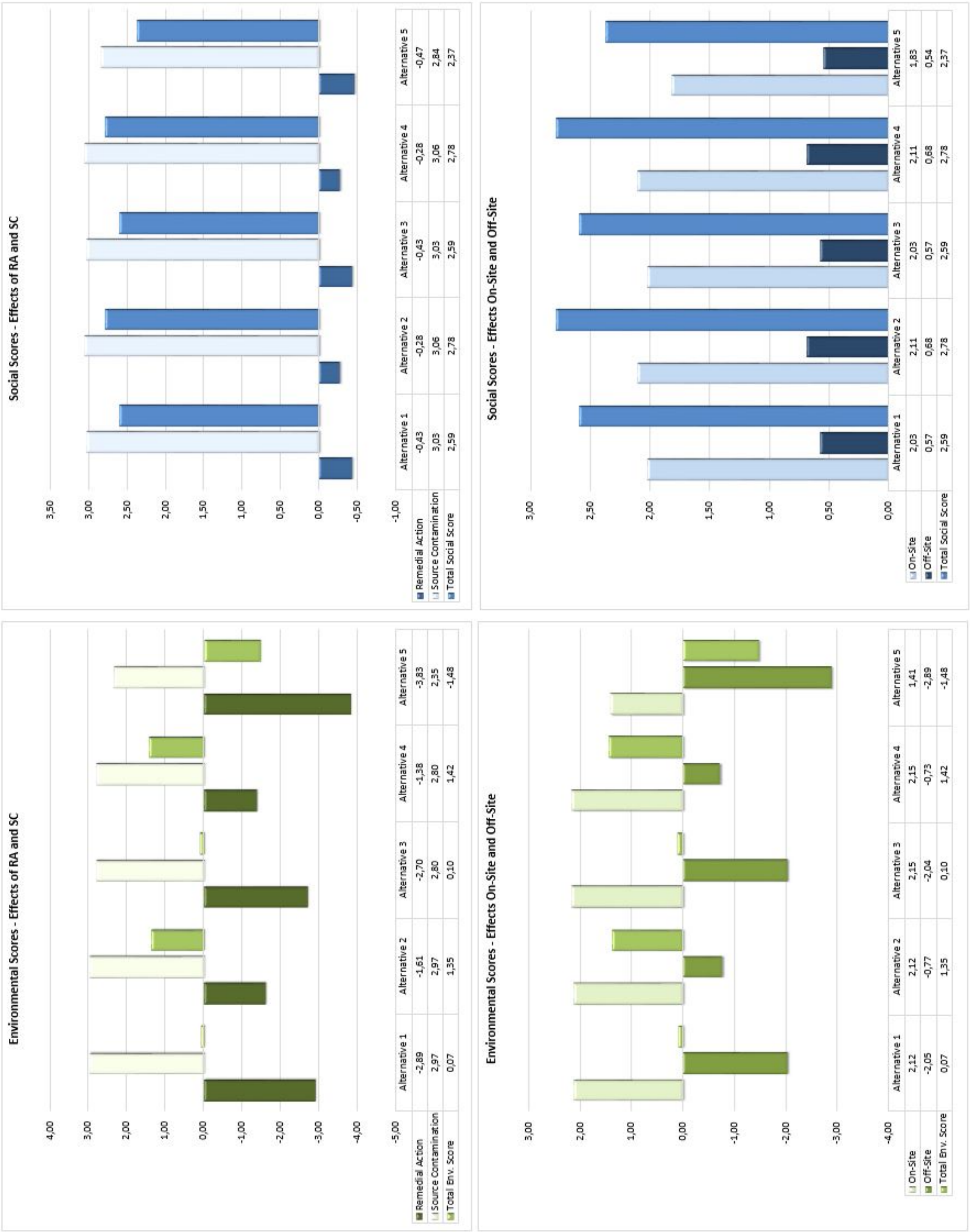


*Figure 26. Sustainability scores for scenario Ia.*

As shown in Figure 27, thanks to the information provided by the model, it is possible to identify where to act in order to improve the score of each alternative. In fact, it is possible to see that all the alternatives have positives effects in the reduction of the impacts of the contamination, but that they have some drawbacks due to the technologies used. Moreover, it can be noticed once again that the negative effects increase with the increase in the amount of soil landfilled. Also, it is possible to see that all the negative effects in the environmental domain are off-site, and that overall positive effects are present both on and off-site in the social domain.



Environmental Scores - Effects of RA and SC

|  | Alternative 1 | Alternative 2 | Alternative 3 | Alternative 4 | Alternative 5 |
|---|---|---|---|---|---|
| Remedial Action | -2,89 | -1,61 | -2,70 | -1,38 | -3,83 |
| Source Contamination | 2,97 | 2,97 | 2,80 | 2,80 | 2,35 |
| Total Env. Score | 0,07 | 1,35 | 0,10 | 1,42 | -1,48 |

Social Scores - Effects of RA and SC

|  | Alternative 1 | Alternative 2 | Alternative 3 | Alternative 4 | Alternative 5 |
|---|---|---|---|---|---|
| Remedial Action | -0,43 | -0,28 | -0,43 | -0,28 | -0,47 |
| Source Contamination | 3,03 | 3,06 | 3,03 | 3,06 | 2,84 |
| Total Social Score | 2,59 | 2,78 | 2,59 | 2,78 | 2,37 |

Environmental Scores - Effects On-Site and Off-Site

|  | Alternative 1 | Alternative 2 | Alternative 3 | Alternative 4 | Alternative 5 |
|---|---|---|---|---|---|
| On-Site | 2,12 | 2,12 | 2,15 | 2,15 | 1,41 |
| Off-Site | -2,05 | -0,77 | -2,04 | -0,73 | -2,89 |
| Total Env. Score | 0,07 | 1,35 | 0,10 | 1,42 | -1,48 |

Social Scores - Effects On-Site and Off-Site

|  | Alternative 1 | Alternative 2 | Alternative 3 | Alternative 4 | Alternative 5 |
|---|---|---|---|---|---|
| On-Site | 2,03 | 2,11 | 2,03 | 2,11 | 1,83 |
| Off-Site | 0,57 | 0,68 | 0,57 | 0,68 | 0,54 |
| Total Social Score | 2,59 | 2,78 | 2,59 | 2,78 | 2,37 |

*Figure 27. Ecological and social effects of the remediation alternatives.*

Figure 28 shows the results in the environmental, social and economic domains and the total normalized sustainability score for scenario Ib.

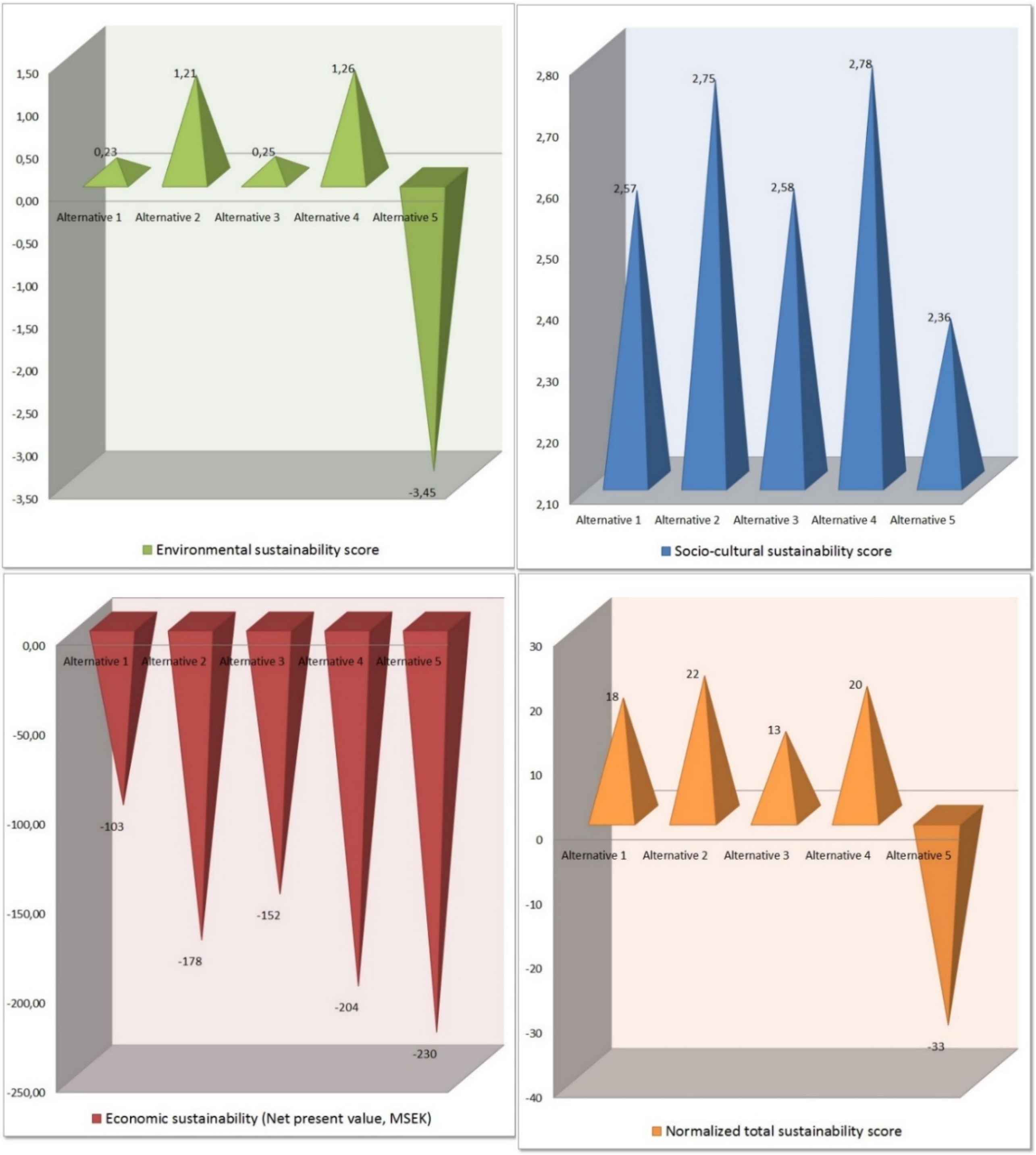
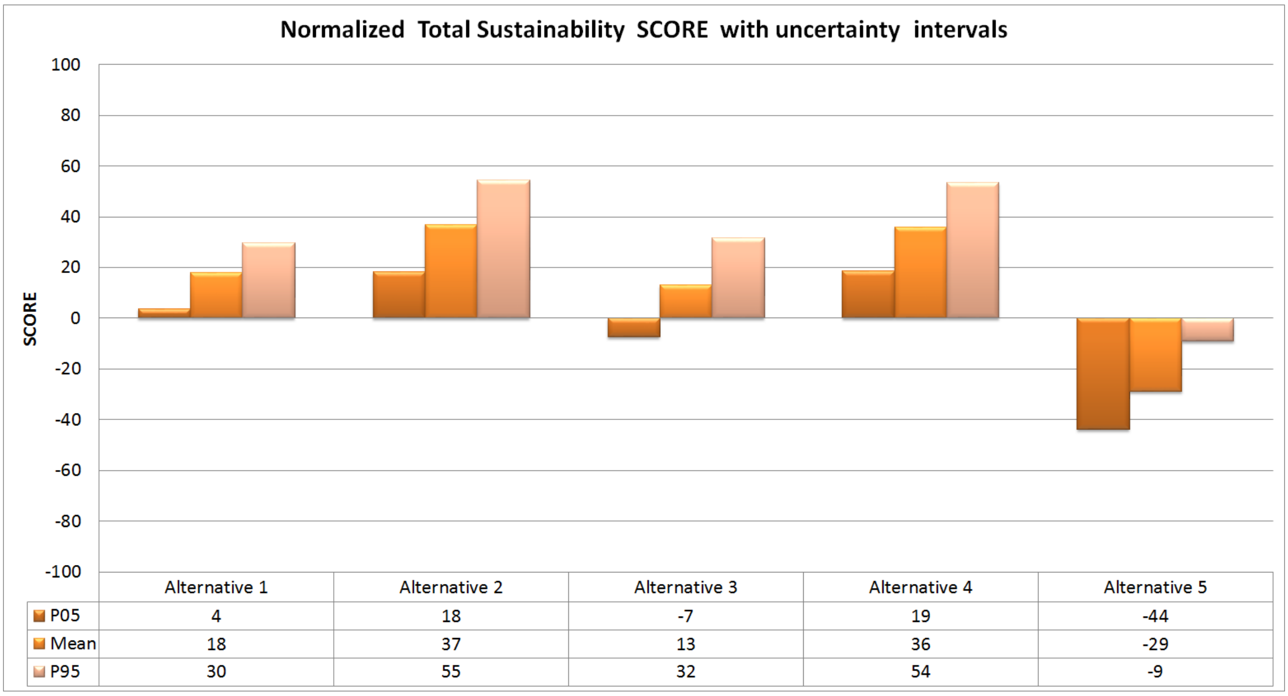


*Figure 28. Sustainability scores for scenario Ib.*

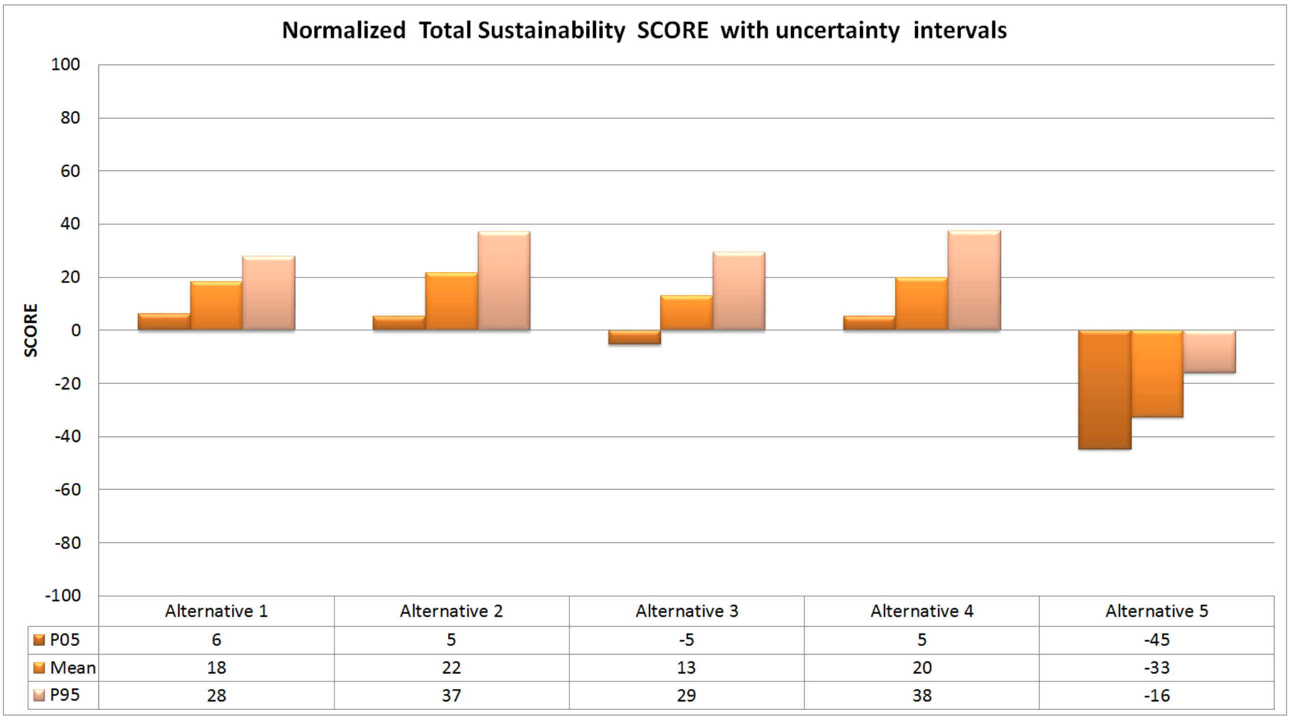
Here, alternative 2 is still the alternative with the highest total sustainability score, followed by alternative 4, but alternative 1 has almost as high total score, followed by alternative 3. Alternative 5 is still the only alternative with a negative total score. Appendix IX shows the ecological and social effects of the remedial alternatives for scenario Ib, but the situation is the same as shown in Figure 27.

Figure 29 shows the normalized total sustainability score with uncertainty intervals for scenario 1a and Figure 30 shows it for scenario Ib. The assessment of the alternatives is associated with substantial uncertainties, however, with a strong certainty that alternative 5 do not have a positive total score and that alternatives 1, 2 and 4 have no negative total score.



| | Alternative 1 | Alternative 2 | Alternative 3 | Alternative 4 | Alternative 5 |
|---|---|---|---|---|---|
| P05 | 4 | 18 | -7 | 19 | -44 |
| Mean | 18 | 37 | 13 | 36 | -29 |
| P95 | 30 | 55 | 32 | 54 | -9 |

*Figure 29. Normalized total sustainability score with uncertainty intervals for scenario Ia.*



| | Alternative 1 | Alternative 2 | Alternative 3 | Alternative 4 | Alternative 5 |
|---|---|---|---|---|---|
| P05 | 6 | 5 | -5 | 5 | -45 |
| Mean | 18 | 22 | 13 | 20 | -33 |
| P95 | 28 | 37 | 29 | 38 | -16 |

*Figure 30. Normalized total sustainability score with uncertainty intervals for scenario Ib.*

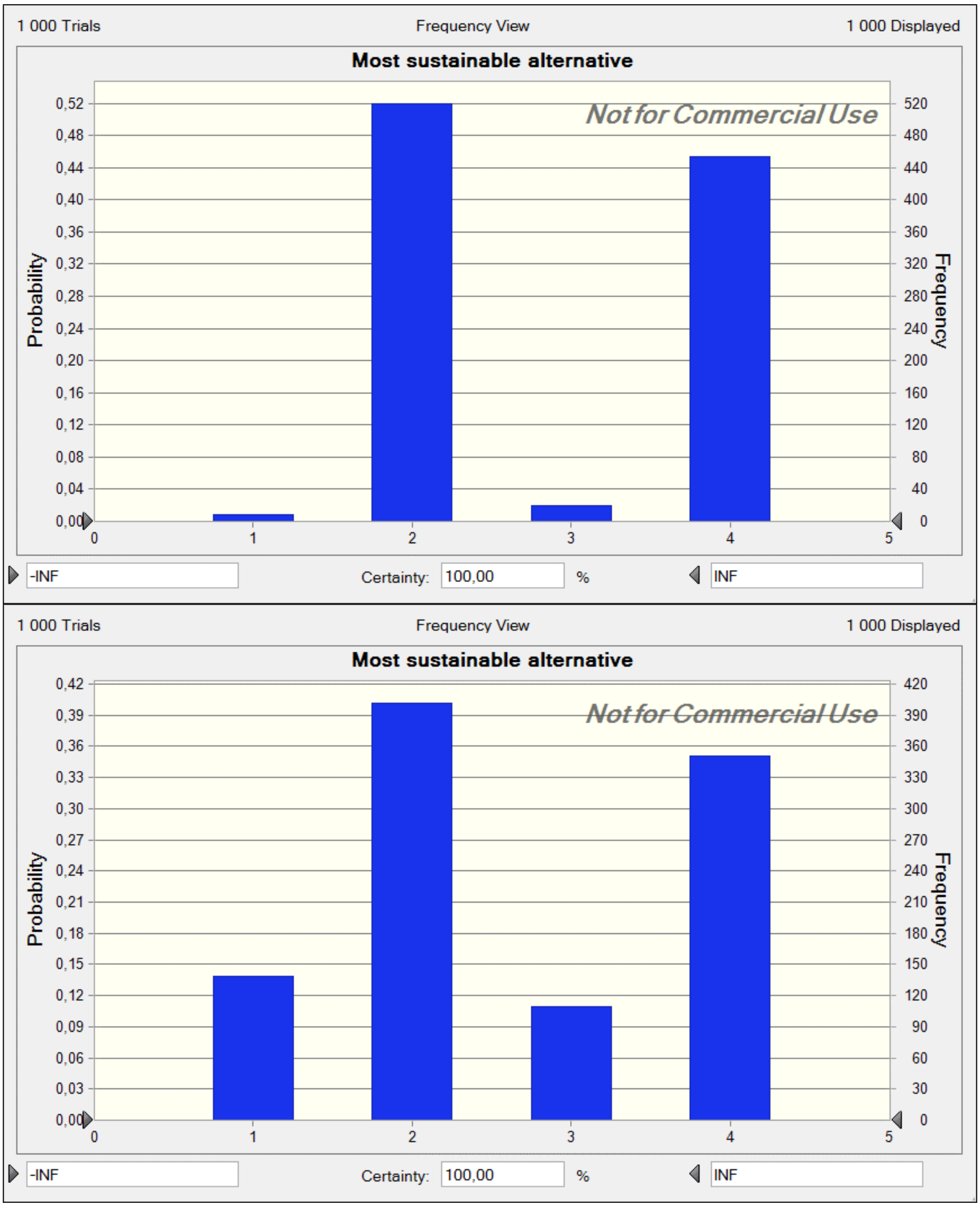
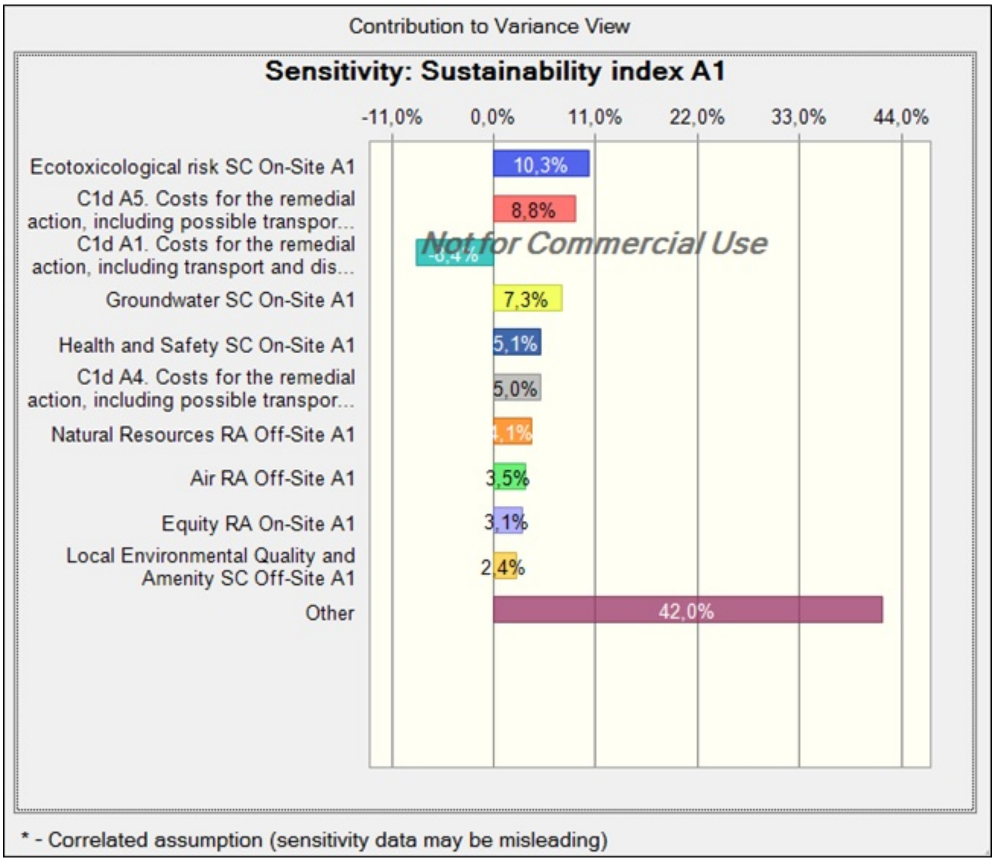
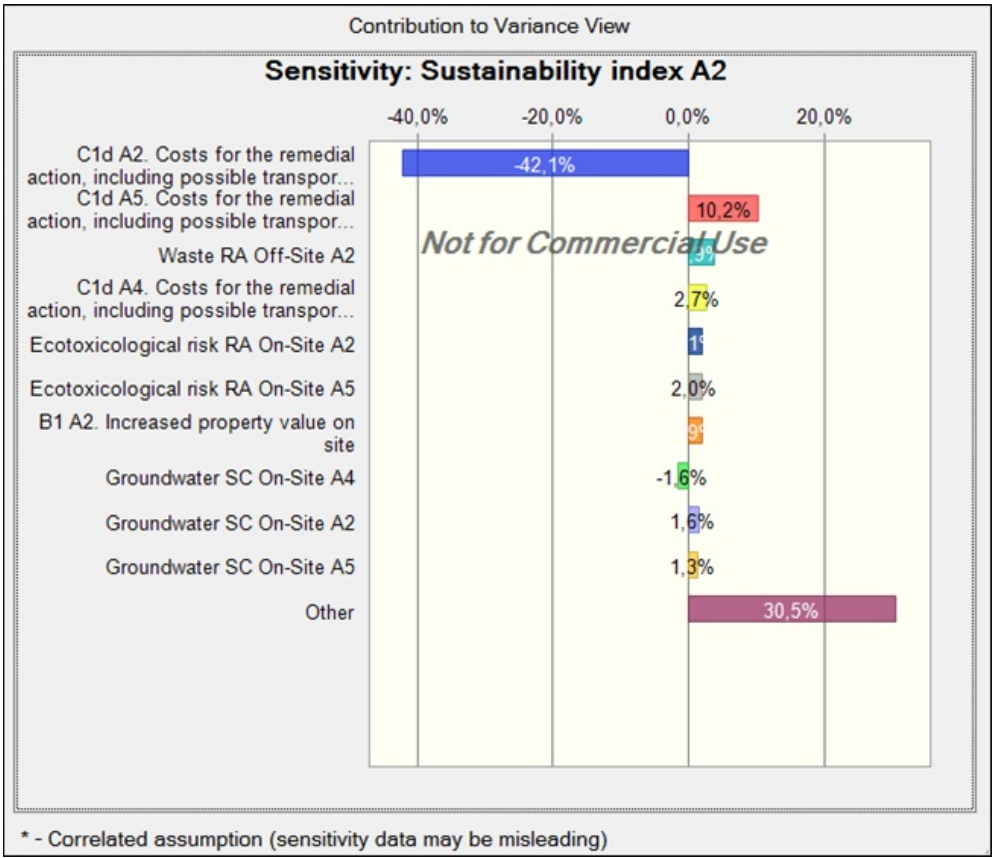


*Figure 31. Probability of each alternative to be the most sustainable in scenario Ia (top) and Ib (bottom).*

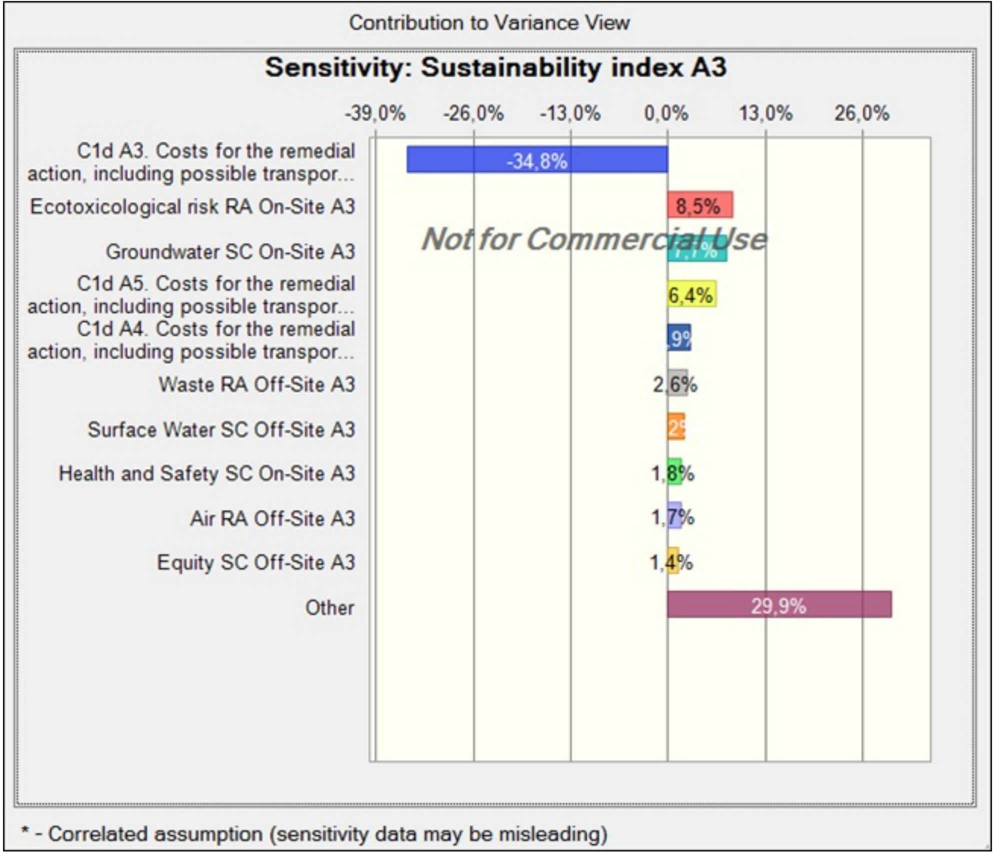
For scenario Ia, Figure 31 shows how alternative 2 has the highest probability of being the most sustainable alternative (almost 52%), followed by alternative 4 (45%), while alternative 1 and 2 having a probability to be the most sustainable ones slightly above 0% (1% and 2% respectively), with no probability of this eventuality for alternative 5. Figure 31 shows also how the probability of being the most sustainable alternative changes for all the alternatives (excluding alternative 5) in scenario 1b: alternative 2 is still the most sustainable alternative but with a lower dominance compared to alternative 4 (40% and 35% respectively) and to the other alternatives (14% for alternative 1 and 11% for alternative 3), while alternative 5 still has no chances of being the most sustainable.

Figure 32 shows which variables contribute the most to the uncertainties of the scores of the five alternatives in scenario Ia. The investment cost is the most influential parameter for each alternative, whereas for alternative 1 it is the investment cost of alternative 5 that slightly influence the uncertainties, due to the fact that low uncertainties are related to the price of this solution. For alternative 1 and 2, where the environmental criteria were associated with low uncertainties, the second most influential parameters are still cost-related, being the cost of alternative 1 itself for the first alternative and the cost of alternative 5 for the second alternative. In addition, there are a number of criteria not related to the CBA that contribute to the overall uncertainty, but with a lower influence compared to the most influential parameters.





* - Correlated assumption (sensitivity data may be misleading)



* - Correlated assumption (sensitivity data may be misleading)

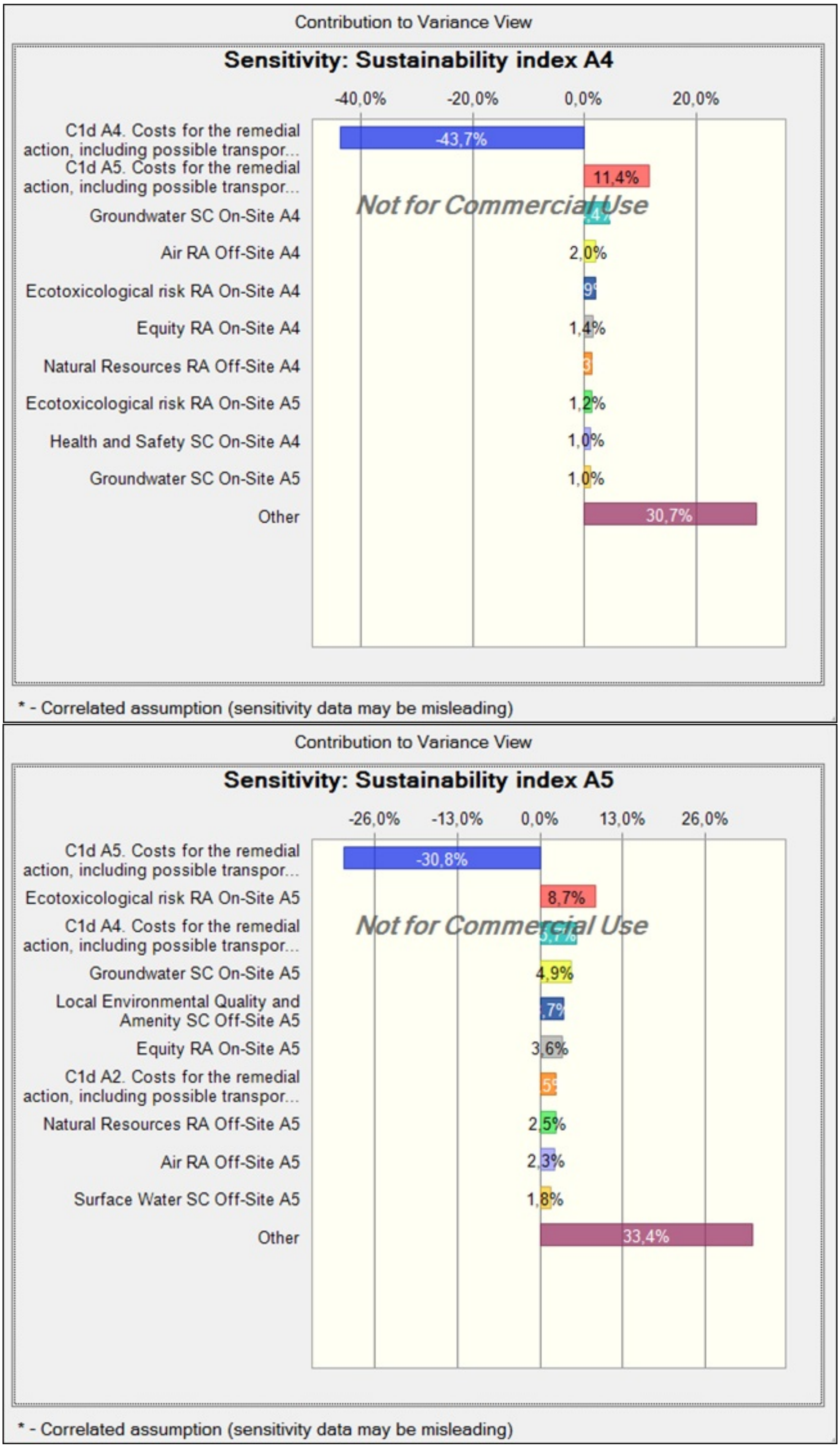


*Figure 32. Sensitivity analysis for scenario 1a. It can be seen which ones are the parameters that influence the uncertainty of the results the most. A=alternative.*

Appendix IX shows the sensitivity analysis for scenario Ib, where the situation was the same as described for scenario a, but with the uncertainty related to the cost of alternative 5 being the second most influential factor for all the alternatives.

## 6.2. Scenario II

In scenario II the environmental domain was considered more important (50%) than the economic and social ones, which had the same relevance (25% each). Here, the scoring and weighting within each domain was the same as for scenario IIa and IIb, and the normalized total sustainability score had the same ranking, even if with slightly different values, due to the fact that the environmental domain influenced the overall result more than before. Figure 33 shows the normalized total sustainability scores for alternatives IIa and IIb.

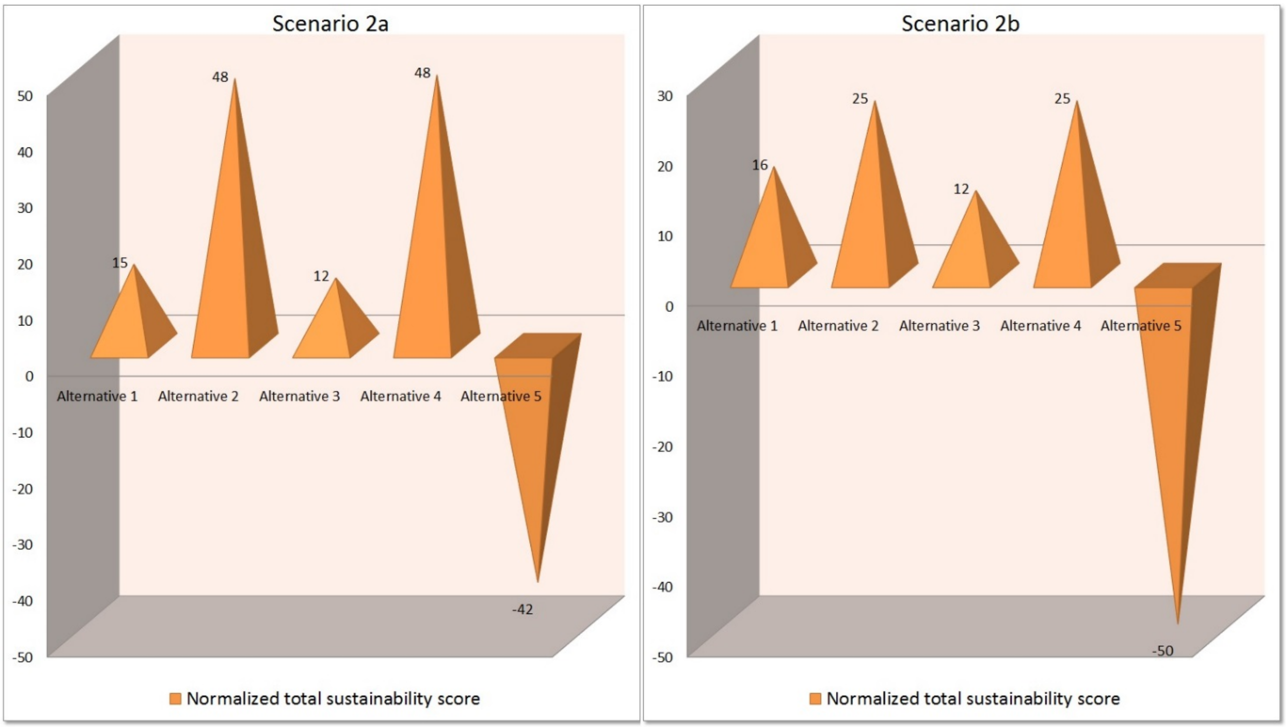


*Figure 33. Total sustainability scores for scenario II (a and b).*

As it is possible to see, in scenario IIa alternative 2 and 4 have exactly the same total sustainability score, more than 3 times higher than the third best alternative (alt.1) and four times higher than alternative 3, while alternative 5 is still the only alternative with a negative score. Scenario IIb shows the same as in scenario Ib: identical situation as seen in scenario IIa, but with lower difference in the score of the highest ranked alternatives and alternative 1 (and 2). It is noticeable that alternative 5 has a very negative score both in scenario IIa and IIb, due to the fact that this solution scored the worst in the environmental domain (the dominant domain in scenario II). The fact that alternative 4 scored as high as alternative 2 is due to the increased weight of the environmental domain, where alternative 4 scored better than alternative 2.

Figure 34 shows the probability of the four alternatives to be the most sustainable ones. In scenario IIa, even though they have the same overall score, alternative 2 has a lower probability of being the most sustainable solution compared to alternative 4 (about 48% versus 52%), with a probability close to 0% for alternative 3 and 0% for alternatives 1 and 5. The fact that alternative 4 has a higher probability of being the most sustainable alternative compared to alternative 2 is explained by the fact that more uncertainties are linked to the score of the environmental criteria for alternative 4 than for alternative 2 (see Table 19) as shown also here in Figure 35 (for scenario IIa). The same reason explains why alternative 1 has higher total sustainability score but lower probabilities than alternative 3 to be the highest ranked: this solution has a lower uncertainty interval than alternative 3, with almost no probability of having a negative score, while alternative 3 has a wider uncertainty interval, with a higher positive interval, that keeps its possibilities to be the most sustainable solution higher than for alternative 1.

In scenario IIb, instead, alternative 2 has a slightly higher probability of being the most sustainable alternative than alternative 4 (47% versus 45%), while alternative 1 has again a lower probability than alternative 3 (3% versus 5%), despite having a higher score (Figure 34).

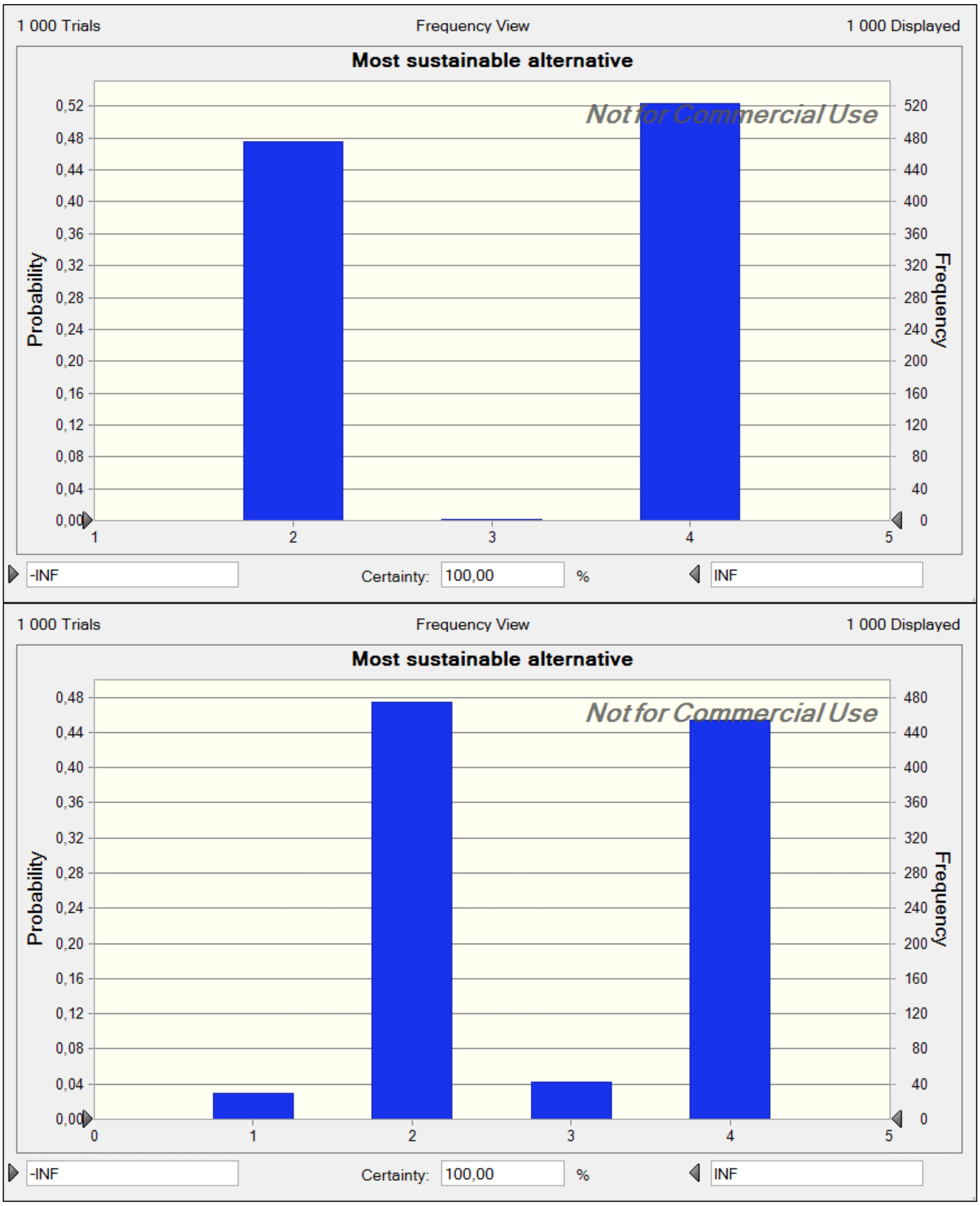
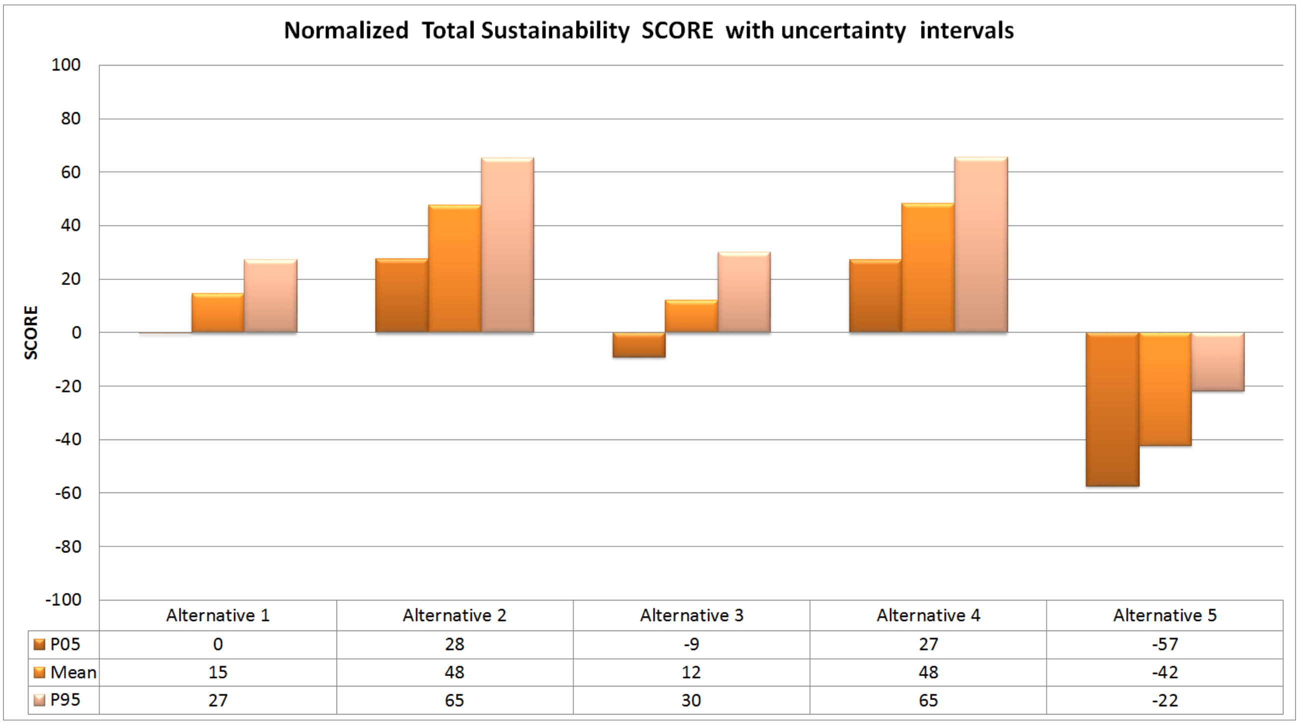


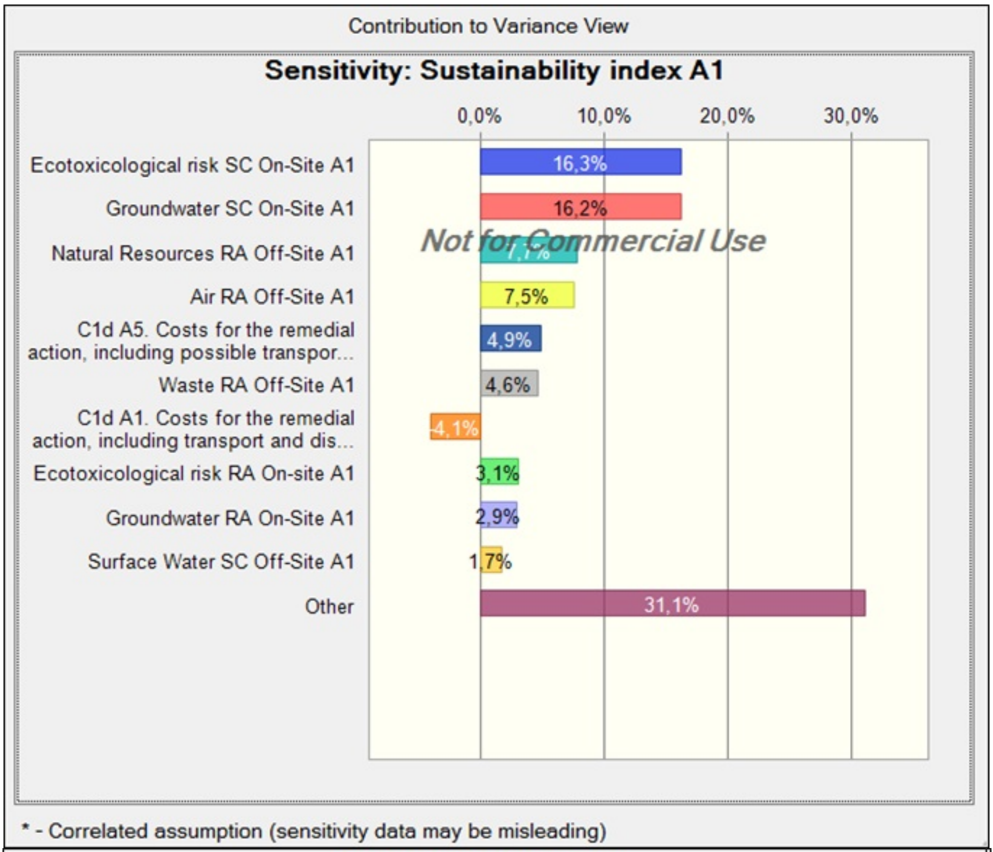
*Figure 34. Probability of each alternative to be the most sustainable in scenario IIa (top) and IIb (bottom).*



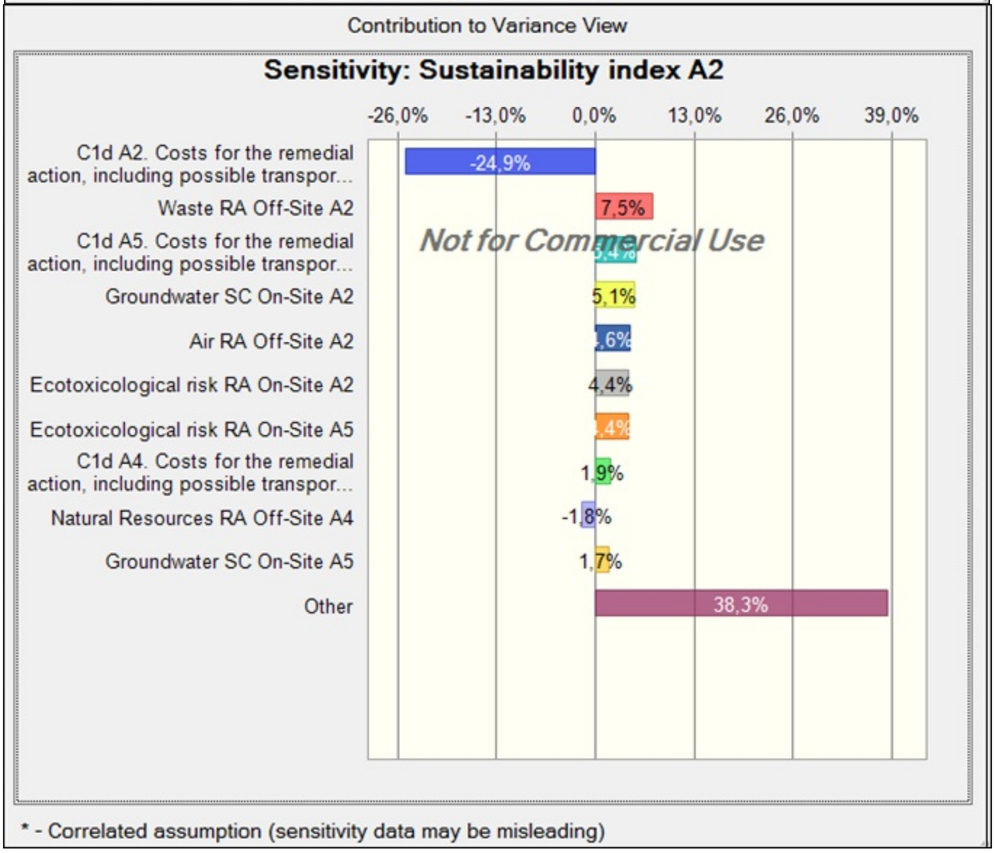
| | Alternative 1 | Alternative 2 | Alternative 3 | Alternative 4 | Alternative 5 |
|---|---|---|---|---|---|
| P05 | 0 | 28 | -9 | 27 | -57 |
| Mean | 15 | 48 | 12 | 48 | -42 |
| P95 | 27 | 65 | 30 | 65 | -22 |

*Figure 35. Normalized total sustainability score with uncertainty intervals for scenario IIa.*

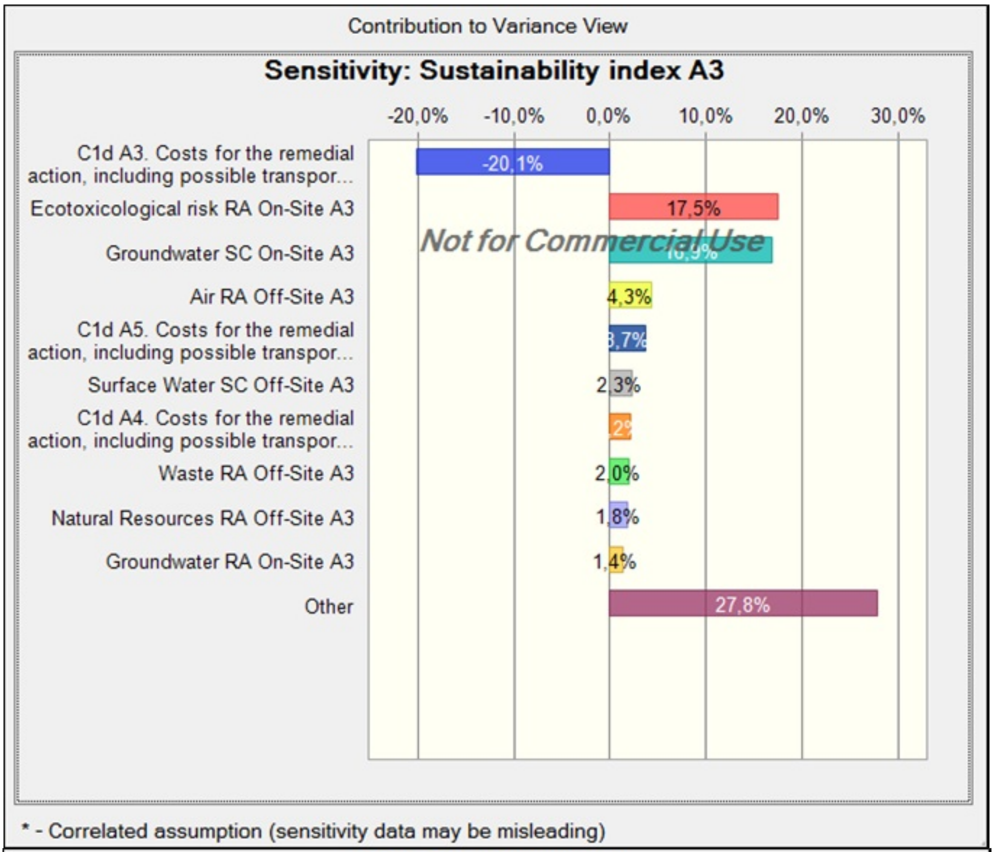
Due to the higher importance of the environmental domain in scenario II, the environmental criteria have a great contribution to the uncertainties for all the alternatives, even though the cost of each alternative is still the most influential factor, apart for alternative 1 in scenario IIa (Figure 36). The sensitivity analysis is shown only for scenario IIa, Appendix IX presents the results for scenario 2b.

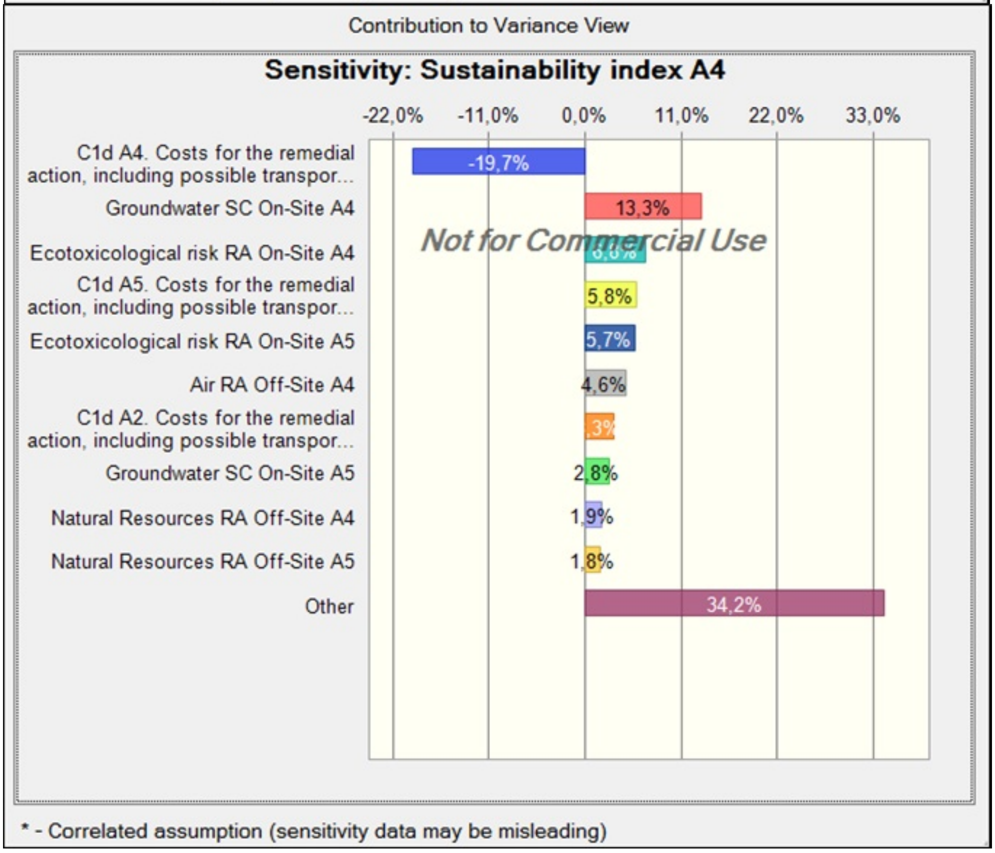


* - Correlated assumption (sensitivity data may be misleading)



* - Correlated assumption (sensitivity data may be misleading)


Contribution to Variance View
Sensitivity: Sustainability index A3
-20,0%
-10,0%
0,0%
10,0%
20,0%
30,0%
C1d A3. Costs for the remedial action, including possible transpor...
Ecotoxicological risk RA On-Site A3
Groundwater SC On-Site A3
Air RA Off-Site A3
C1d A5. Costs for the remedial action, including possible transpor...
Surface Water SC Off-Site A3
C1d A4. Costs for the remedial action, including possible transpor...
Waste RA Off-Site A3
Natural Resources RA Off-Site A3
Groundwater RA On-Site A3
Other
-20,1%
17,5%
16,9%
4,3%
3,7%
2,3%
2%
2,0%
1,8%
1,4%
27,8%
Not for Commercial Use
* - Correlated assumption (sensitivity data may be misleading)


Contribution to Variance View
Sensitivity: Sustainability index A4
-22,0%
-11,0%
0,0%
11,0%
22,0%
33,0%
C1d A4. Costs for the remedial action, including possible transpor...
Groundwater SC On-Site A4
Ecotoxicological risk RA On-Site A4
C1d A5. Costs for the remedial action, including possible transpor...
Ecotoxicological risk RA On-Site A5
Air RA Off-Site A4
C1d A2. Costs for the remedial action, including possible transpor...
Groundwater SC On-Site A5
Natural Resources RA Off-Site A4
Natural Resources RA Off-Site A5
Other
-19,7%
13,3%
5,8%
5,7%
4,6%
3%
2,8%
1,9%
1,8%
34,2%
Not for Commercial Use
* - Correlated assumption (sensitivity data may be misleading)

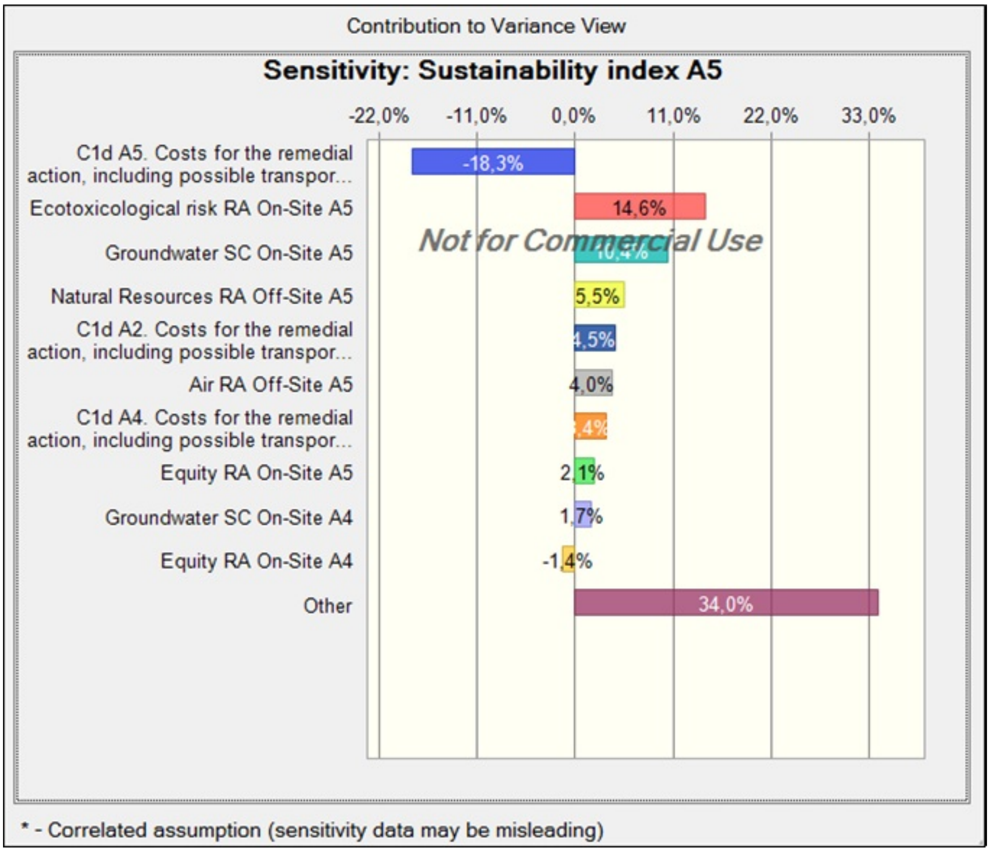


*Figure 36. Sensitivity analysis for scenario IIa.*

## 6.3. Scenario III

Scenario III was set having the economic domain contributing the most to the results (50%), followed by the environmental (33%) and social (17%) domains. The results in Figure 37 show how influential this change in the domains weighting influenced the results.

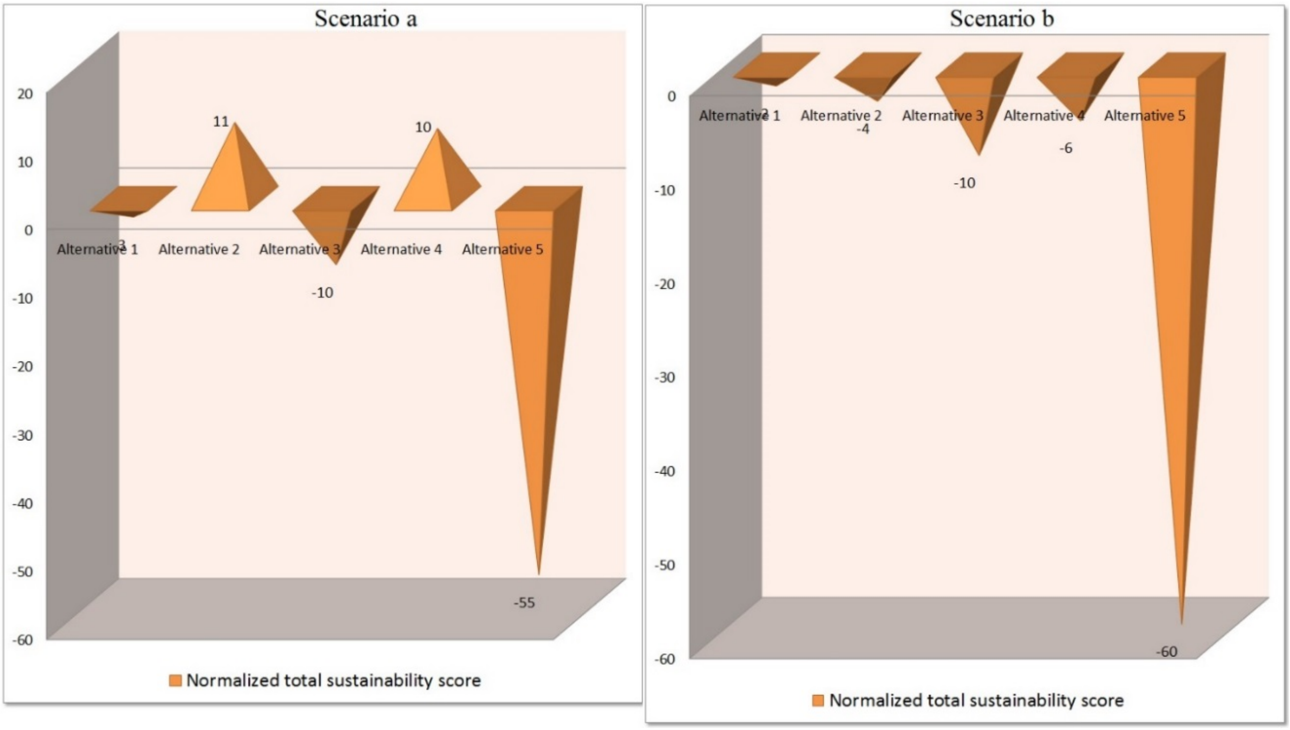
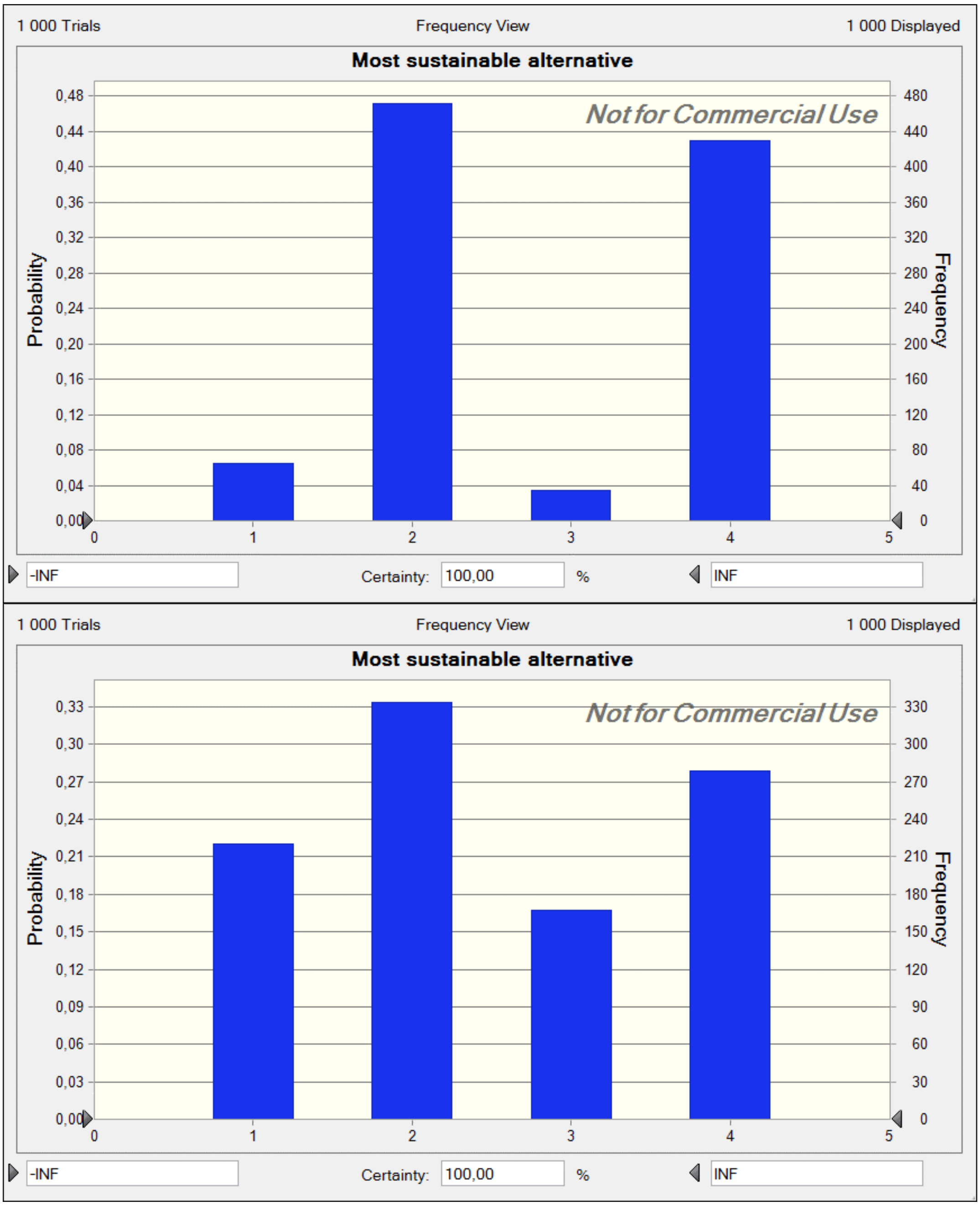


*Figure 37. Total sustainability scores for scenario III (a and b).*

Due to the negative NPV for all alternatives, the total scores are much lower both in scenarios IIIa and IIIb, with scenario IIIb resulting in not showing any option with a positive total sustainability score. In scenario IIIa, the situation regarding the scores is the same as for scenario I and II (alternative 2 being the most sustainable with alternative 4, followed by alternatives 1 and 3, with alternative 5 having the lowest score) with the difference that now also alternative 1 and 3 do not receive a positive total score, similar to alternative 5. In scenario IIIb all the options scored negatively, due to the fact that truck transport implies lower environmental scores and higher costs (and lower NPVs as a consequence). Here, alternative 1, which is the less expensive option, has the highest score, followed by alternative 2, 4, 3 and 5.

Figure 38 shows that alternative 2 and 4 have still the highest scores in scenario IIIa, with alternative 2 having the highest probability of having the major score (47% alt.2 versus 43% alt.4), while alternatives 1 and 3 having a low probability of it (7% and 3% respectively) and alternative 5 having again 0% probability of scoring the best. In scenario IIIb, alternative 2 and 4 have again the highest probabilities of being the most sustainable options (33% and 28% respectively), although they do not have the highest score, followed by alternative 1 and 3 (22% and 17% respectively). This is due to the fact that alternatives 2 and 4 have a wider uncertainty interval than alternative 1 and 3, also with higher 95-percentile values, as shown in Figure 39 (just for scenario IIIa). The fact that alternative 1 has the highest NPV and that the economic domain is the most important in scenario III strongly influenced the results.

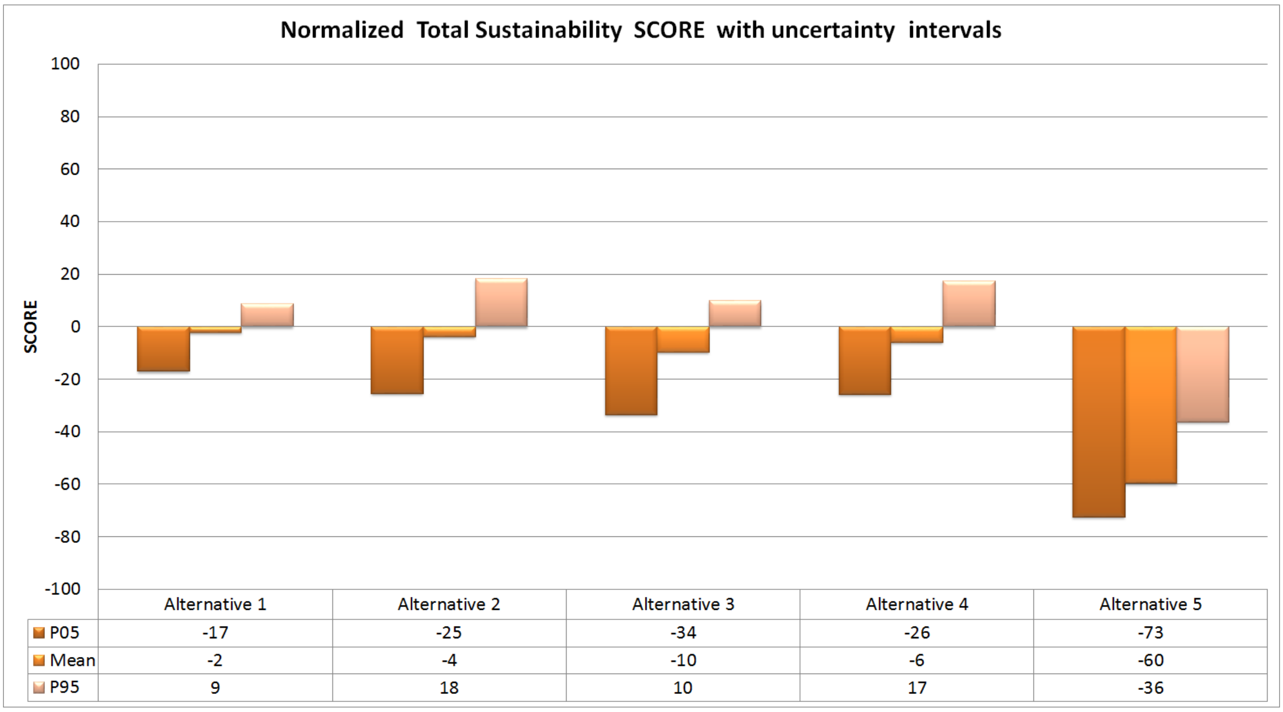
Being the economic domain the most influential in the analysis for this scenario, the parameters that weighted the most on the uncertainties are the costs of the alternatives. Appendix IX shows the sensitivity analysis for scenarios IIIa and IIIb.



-INF Certainty: 100,00 % INF

-INF Certainty: 100,00 % INF

*Figure 38. Probability of each alternative to be the most sustainable in scenario IIIa (top) and IIIb (bottom).*



| | Alternative 1 | Alternative 2 | Alternative 3 | Alternative 4 | Alternative 5 |
|---|---|---|---|---|---|
| P05 | -17 | -25 | -34 | -26 | -73 |
| Mean | -2 | -4 | -10 | -6 | -60 |
| P95 | 9 | 18 | 10 | 17 | -36 |

*Figure 39. Normalized sustainability scores with uncertainty intervals for scenario IIIa.*

## 6.4. Other scenarios

Figure 40 shows how the probability of score the highest changes for all the alternatives depending on the type of scenario chosen. Noticeably, alternative 2 has the probability to score the highest in all the scenarios but one, always followed by alternative 4, and alternative 5 has no probability of being the alternative with the highest score in all the different scenarios. The 'boat vs truck' scenario is not included, due to the fact that the alternatives assessed are not the same as in the other scenarios.

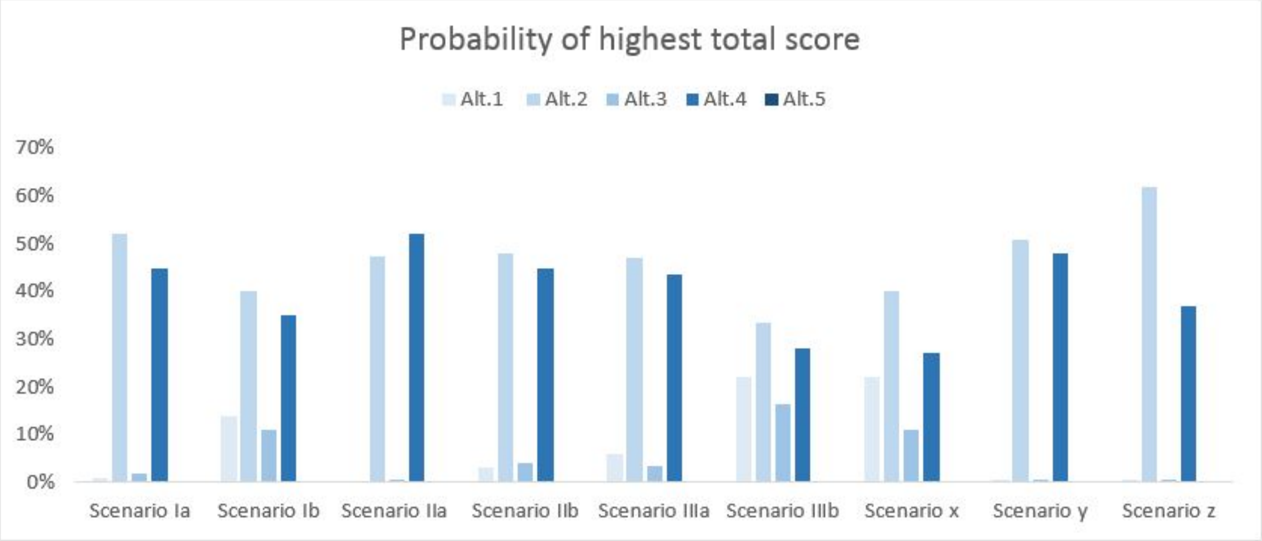


*Figure 40. Probability of the five alternatives to score the highest in the different scenarios analysed.*

# 7. Discussion

## 7.1. Results of the case-study

The results show that in all the main scenarios alternative 2 (1m excavation + S/S + ISCO) and alternative 4 (1m excavation + S/S + bioremediation) are the ones that received the highest total scores. This is also strengthened by the sensitivity analysis, which shows that these two remedial actions have the highest probabilities to be the options that come out with the highest total score in all the different scenarios. This is due to the fact that these two alternatives scored better than the others in the environmental domain, mostly because of the lower amount of soil excavated and landfilled, a feature that highly influenced the criteria related to the effects on air, non-renewable natural resources consumption and non-recyclable waste production (E6, E7 and E8), where the biggest differences were present. These results reflect what was pointed out at the beginning of the project, namely that landfilling of the excavated contaminated soil is not the most sustainable solution both in the short and in the long term to remediate contaminated sites, and that in-situ techniques should be employed more often (Allen, 2001; Bardos, et al., 2010).

It is noticeable that, regardless of which scenario is adopted, alternatives 2 and 4 always come out as the highest ranked options, although the actual total score differs. In scenario III, where the economic domain is wheighted the most, the total scores are negative, which could give the impression that all the alternatives would be unsustainable options. Nevertheless, it has to be kept in mind that the score depends on how the normalisation and the calculation of the sustainability index is made, therefore a negative score does not mean that the alternative is not sustainable: the ranking is the most important output of the analysis, not the values. Also, it is always difficult to define what is sustainable and what is not, because the specific definition of sustainability can change depending on the boundaries of the analysis, on minimum criteria to fulfill and other site-specific constraints.

Thanks to the features of the SCORE method it is possible to understand which criteria have to be improved for each remedial action to increase the score and meet eventual specific definition of sustainability (Rosén, et al., 2015). In fact, it is possible to see that all the alternatives have positive effects in the reduction of the impacts of the contamination, but that they have some drawbacks due to the technologies used. Moreover, it can be noticed once again that the negative effects increase with the increase in the amount of soil landfilled. Also, it is possible to see that all the negative effects in the environmental domain are off-site, and that overall positive effects are present both on and off-site in the social domain (Figure 27 and Appendix IX). Therefore, it can be argued that to increase further the performance of the winning alternatives, one can focus on the reduction of negative effects off-site caused by the remedial actions on the environment. One way of doing it could be decreasing the air emissions, that could be obtained looking for a place where to get the pristine soil close-by the landfill or on the way to the landfill, in order to eliminate the empty trip from the landfill to the site and all the emissions related to going to get pristine soil somewhere else. Another way to decrease the air emissions could be to use more environmentally friendly fuels, such as low sulphur fuels for the boat transport. Also, it would be effective to find a way to increase the share of the excavated soil that could be reused as filling material on-site, decreasing, as a consequence, the amount of soil to be landfilled and substituted by pristine soil, having thus a positive effects on the air emissions and decreasing the amount of waste produced.

Something more that is possible to see from all the previous results is that they show what was already stressed out throughout all the report, i.e. the paramount importance of having precise and reliable data. Indeed, the sensitivity analysis showed how the results were highly influenced by the uncertainties related to the investment cost of the different alternatives. Therefore, the sensitivity analysis, showing which parameters influenced the results the most, provided useful information regarding what could be done in order to improve the quality and reliability of the input data: in this project, it is crucial to investigate more in depth the economic part of the remedial actions studied, since it might change the result of the assessment. Moreover, due to time and data constraints, the long-term costs and benefits linked to the remedial actions with regard to effects on human health and environmental quality were not investigated. For a full CBA, such externalities should be included and could show more complete results.

In order to analyse to what extent the level of uncertainties assigned in the economic criteria of this analysis influenced the results, a simulation where all these uncertainties were set to 'low' was run (scenario y): this would be the case if the cost of each alternative and the benefits due to the remediation were clearly defined, as well as the cost of the externalities. The results of the analysis, presented in Appendix X, showed that the ranking of the alternatives was not influenced, even if the total sustainability score were slightly lower than before. Therefore, the results would be influenced by changes in the economic domain only if new data would change the NPV of the different alternatives, not only if the present data would just be confirmed and the uncertainties lowered.

## 7.2. Weighting of the environmental criteria and sub-criteria

The selection of which kind of scenarios to consider was done according to the fact that scenario I, where all the domains have the same weight, is the most common way to perform sustainability assessments (Rosén, et al., 2015), scenario II implies that the environmental domain is more important than the others, based on the concept that without it humans cannot exist (Rosén, et al., 2015), while scenario III, that gives more importance to the economic criterion than to the environmental one, was considered interesting in order to analyse also a more business-oriented point of view.

In this project, the selected weighting of the environmental criteria and subcriteria give great importance to the secondary effects (i.e. negative effects of the remediation alternatives on and off-site), feature that differs from the traditional SCORE assessment (Rosén, et. Al, 2015; Anderson, et al., 2018). This kind of scenario is similar to what was described in Anderson, et al., (2018) as 'Public-Green' scenario, with the difference that also the secondary effects of the remedial action on soil, groundwater and surface water are taken into account. This weighting scenario was chosen in order to include in the assessment the secondary effects of remediation on local, regional and global scale, showing how influential they can be in a sustainability assessment. Also, these effects were the ones scored by the author and with the new methodology, while the others (i.e. effects of the remediation on the source of contamination) were based on assumptions.

However, it seemed interesting to see how the results changed performing a traditional SCORE analysis (Scenario x, shown in Appendix X). The results showed that the alternative with the highest score was once again alternative 2, now followed by alternative 1 and alternative 4 with similar scores. Nevertheless, Figure 40 showed that the probability of each alternative to score the highest was still higher for alternative 2 and 4 compared to the others. This shows that the way the secondary effects are taken into account in a SCORE analysis could influence the outcome of the sustainability assessment, therefore a common methodology to include them should be developed and accepted by practitioners.

## 7.3. Sustainability and transport scenario

It is not possible to compare the results from the two different transport scenarios (a and b) and then decide if it is more sustainable to use boats or trucks to landfill the soil. If compared in this way, it might seem that transporting the soil to a landfill by boat is better than doing it using trucks, because of their higher scores, but it has to be kept in mind that some inputs are based on normalized values (such as the ones from SimaPro + Web HIPRE) and as a consequence the normalized scores given from SCORE provide a realtive ranking of the analysed alterantives (Rosén, et al., 2015), making the two results not comparable.

However, it seemed interesting to understand if it is more sustainable to combine the use of truck and boat transport or just truck transport. Therefore, an additional scenario was analysed, where the domains, criteria and subcriteria were weighted as for scenario I, and the alternatives considered were the ones with the highest scores from the previous analyses, i.e. 5 m of excavation + S/S + ISCO and 5 m of excavation + S/S + bioremediation, for both the scenarios with truck and boat transport and only truck transport (alternative 2a, 4a, 2b and 4b). All the criteria were scored the same as in the other analyses, but not criteria E6 and E7, which results were dependent on the normalization used. Description of this scenario can be found in Appendix X. The normalized total sustainability score shows that there is no difference between the two types of transport of the contaminated soil for alternatives 2a and 2b, and little difference for alternative 4a and 4b (Appendix X). However, the process selected in SimaPro to model the boat transport implied that the boat would use the classic bunker fuel, therefore it can be argued that the boat transport would be more convenient if a more environmentally friendly type of fuel would be used.

## 7.4. Double-counting

Double-counting is a problem that is often present in MCDA, and that SCORE method tries to handle (Rosén, et al., 2015). Going through the different criteria, it might seem that some overlapping is present between the environmental, social and economic criteria (or subcriteria), such as the emissions due to the transport, that are taken into account in the environmental domain by the air criterion (E6), in the social by the health and safety criterion (S5) and in the CBA in the quantification of the impaired health due to the remediation action (C2). However, it has to be noticed that the economic criterion has a utilitarian basis, while the environmental and social ones have a 'deontological' basis, and therefore they analyse the same aspect from different point of view and give therefore different outcomes.

The environmental criterion handles the air emissions as equivalents of some indicators ($CO_2$ equivalents, $SO_x$ equivalents etc.) and use these values to rank the alternatives according to the amount of pollutants emitted. The social aspect focuses (among the other things) on the emissions of each remediation alternative but takes into account also wider aspects, such as the location of the site (e.g. contribution to air quality due to emissions from trucks would be higher in a large project located in a small community than in a big city as Stockholm), eventual receptors affected by the negative effects of such emissions and other features. The economic criterion simply transforms these emissions from pollutant-equivalents to monetary term, in order to better describe the real NPV of each alternative. It is important to highlight this aspect in order to make the results and the steps that led to the results as transparent as possible, so they can be used in the decision-making process and understood by all the stakeholders involved. Hence, it can be stated that double-counting was not an issue in this project, because the criteria were handled accordingly to what stated above.

## 7.5. Assumptions

As already mentioned in the report, some assumptions were needed and it is important to analyse them in order to fully understand the results of the sustainability assessment. Most of the assumptions that were made depended on the data available at the time this project was carried out and they can be divided in two groups: related to the site and related to the remedial actions.

Regarding the site, it is indubitably important to consider that the analysis was based on a conceptualized site and not on the real one, especially to use these results in the decision-making process for Kolkajen-Ropsten project. Thus, some of the assumptions related to this conceptualization of the site need to be further described. First and foremost, it has to be considered that this site has a considerable size (75 000 $m^3$ of contaminated soil): in the assessment, it was assumed that the site is homogenous, while it is seldom the case in the reality, and especially not so for the Kolkajen site.

Therefore, it is interesting to consider how to implement SCORE for a real case and if the assessment carried out in this project can be considered reasonable. In a real case, where the geology would be more complex than the one shown in the conceptual model, the site could be either divided in sub-areas and each of them could be assessed separately in the same way that was done for the whole area in this work, or the site could be considered as a whole and each of the studied remediation alternatives consisting of different techniques together. In both these scenarios, the work done in this project would be helpful, because it shows how to compare remediation alternatives that include the use of different methods and it presents a methodology to include in-situ and ex-situ techniques together (but also separately) in the SCORE framework, and it shows already that innovative in-situ techniques are more sustainable than the classic excavation and landfilling.

Regarding the remedial actions, the first fundamental assumption was related to their efficiency in treating the contamination, because all of them were considered to meet the clean-up goals at the same level. Only ISCO was tested twice at the site and proved to be a good and practicable solution, while bioremediation was (positively) tested only once and some uncertainties are still related to its time requirements and efficiency. S/S and ISTS, instead, were not tested at the site, but considered potential solutions by experts and literature. This assumption was necessary in order to be able to compare the different alternatives in the sustainability assessment subject of this project, because the lack of data due to the early stage at which the real project was at the time this study was carried out did not enable to use real data regarding the efficiency of each technology in meeting the clean-up goals.

Despite this assumption did not influence the process of developing a new methodology to assess in-situ techniques in the SCORE method, it had an effect on the results of the assessment. As shown in Section 6, the alternatives that include the extensive use of in-situ technologies have always the highest score, while in-situ thermal remediation has always the lowest score. However, if more precise or real results were available regarding the ability of each technique to meet the remediation goals, it would probably be the case that excavation and thermal remediation would be the techniques to have the highest probability and ability to meet the remediation goals. In fact, in-situ techniques such as ISCO and bioremediation are usually associated which higher uncertainty in successfully treat contamination than other common and more widely used techniques (Gomes, et al., 2013; Kuppusamy, et al., 2016). Therefore, in a case-study where these factors would be kept into consideration, the sustainability assessment might give different results regarding the ranking of the five studied alternatives, increasing the scores of excavation and in-situ thermal solidification. However, this assumption for the purpose of this project was considered to be reasonable. That is because if the alternatives would not meet the remediation goals they would not be used at the site, and therefore they would not be included in the assessment.

A good way to show that in-situ techniques are usually linked with more uncertainties than the classic ex-situ techniques could be assigning higher uncertainties to the criteria and sub-criteria that describe the effectiveness of these technologies to meet the remediation goals. In this project, however, the uncertainties were assigned according to availability of site-specific data, meaning that the lower was the amount of data available for a technology, the higher was the assigned uncertainty. Nevertheless, in future projects, the way to assign uncertainties could be a mean to describe the reliability of the technology used.

The assumptions needed to perform the LCA could also have influenced the scoring of some of the environmental criteria: here, some assumptions were necessary when modelling the production of the chemicals, because due to industrial secrecy some information were not available (such as the energy needed to mix the chemicals to create products such as PersulfOx or the ORC solution). Also, some data, such as information related to the production of certain chemicals, were not available on the

LCA databases, deeming it necessary to use data about similar chemicals. These required simplifications were based either on literature data or on expert opinions and considered to have a lower relevance on the overall results than other parameters present in the assessment. Therefore, their use can be considered justified, even though it is not really clear to which extent they influenced the results of the LCA.

Simplifications were also necessary with regard to which part of the remediation technologies to include in the streamlined LCA in SimaPro: only the major drivers of the impacts were included (identified from the literature), while other characteristics were omitted. However, it has to be remembered that some of the features of the different in-situ and ex-situ technologies left out from the assessment could have had some influence in certain output categories from SimaPro, such as mineral resource scarcity that would have been influenced by the materials used above the ground level, and also the fact that in the modelled processes the waste scenarios were not considered. Therefore, these assumptions and simplifications made it necessary to select only certain outputs from SimaPro to be used in SCORE, because the information left out could have influenced other categories and therefore undermined the reliability of the results if used to score the environmental criteria. However, in the future, it might be interesting to assess which categories could be included in the assessment if a complete LCA would be performed, and how beneficial it would be to invest time and resources to implement it against a streamlined LCA with regard to the precision and reliability of the results of the SCORE assessment.

## 7.6. The new method to score the environmental criteria

In this project, a new method to include the assessment of in-situ techniques was developed and applied to a case-study, as described in Section 3 and shown in the application in Section 5. The strength of the method is that it can be used to assess any kind of remediation technique (in-situ vs in-situ, in-situ vs ex-situ, ex-situ vs ex-situ), even if they imply the use of different technologies. The application of this methodology requires the availability of many information and data regarding the techniques assessed, some not easy to collect and/or based on assumptions, and the results strongly depend on their goodness and quality.

Being at its first application, this method can still be improved. It can be argued that the sub-subcriteria used to score the secondary impacts of the remedial action on soil, groundwater and surface water (same procedure would be used for the sediments) could be extended, in order to better describe these impacts. For example, the sub-subcriterion that describes ‘other’ eventual negative environmental effects could be further divided in more precise categories, in order to describe eventual effects of the alternatives assessed. However, it is not an easy task, since the wide selection of remediation technologies existing imply very different secondary impacts, and it might be difficult to find common impact categories for all of them. It could be considered to implement a selection of various categories as sub-subcriteria, which can be taken in consideration or disregarded during the score depending on the relevance for the remediation technologies assessed.

Moreover, the scoring of these particular sub-subcriteria is based on literature and case-studies, therefore the data is as precise as comprehensive is the literature on the subject. Here, the risk is that the drawbacks of new technologies might be not yet identified or present in the literature, undermining the goodness of the scoring. Finally, the sub-subcriteria selected for the quantitative scoring of the secondary impacts on air, non-renewable natural resources and waste generation could be further improved if a complete LCA would be performed, as already mentioned before.

## 7.7. Factors influencing the decision-making

Overall, even if this is a study of an idealized site, from the results of the SCORE analysis it can be strongly advised that eventual further studies should focus on how to efficiently implement the alternatives involving excavation of the first meter of the ground, solidification/stabilization from 1 to 5 meters b.g.l. and in-situ chemical oxidation (alternative 2) or bioremediation (alternative 4) at Kolkajen site. Nevertheless, apart from the results of the sustainability assessment with the SCORE method, other characteristics of the remediation alternatives could influence if they would be or would not be chosen as the solutions to be implemented. The two most important can be linked to 1) the budget available and 2) the time frame necessary to remediate the site for each technique.

In the first case, the cost to implement the most sustainable alternative could exceed the budget available for the project and force the decision maker to choose a less sustainable alternative. In this project, as can be seen in Section 5.6, there is a substantial difference in the price of the different alternatives: the two that score the highest, alternative 2 and 4, have NPVs that differ of about 15 to 20 MSEK, where the difference is even bigger in respect to alternative 1 (5 meters of excavation + ISCO) and 4, with the latter having a NPV 50 MSEK more negative than alternative 1. Scenario III shows the difference in the results if more weight is given to the economic domain than to the others, where the options with the highest NPVs gain positions in the ranking. However, considering the size of the whole project in which the remediation of Kolkajen-Ropsten site is present, it can be argued to which extent 20 MSEK of difference between the alternatives that scored the highest can be considered a feature important enough to lead the decision towards the cheapest option, or if there might be other characteristics more influential for the decision-making process.

Therefore, it is more important to investigate the efficiency of the different remediation methods in respect to the time. Often, in remediation projects relating to exploitation, time is a major driver in choosing which techniques to implement. Here, the five different techniques have different time requirements for remediating the site. Excavation, present in all the alternatives, can be considered a fast technique (as shown as an example in Suer & Andersson-Sköld, 2011) and therefore not the driver of the remediation length. In-situ chemical oxidation is a relatively fast technique that can be expected to treat the contamination in less than a year (9-12 months according to Kemakta, 2016), thermal stabilization is also a very fast technique, with time efficiencies in term of months (as shown in the case studies from the Federal Remediation Technologies Roundtable, FRTR, 2018). Instead, bioremediation performed with the use of oxygen-releasing compounds is a technique that can be slow, that might need from months to years to effectively treat the contamination (FRTR, 2018). In this project, based on data from Kemakta, 2016, from literature and from expert opinion of people involved in the Kolkajen project, it was selected 9-12 months as a time required for the alternatives involving ISCO to be efficient, 6-9 months for thermal stabilization and 24-36 months for bioremediation. While the uncertainties related to the time needed for the first two technologies to be effective are low, the uncertainties about the time requirements for the bioremediation in alternatives 3 and 4 are instead much higher. Alternative 4 always is always the second highest ranked alternative in this assessment, with considerable probabilities of being the highest ranked, but here the time factor could influence the decision towards choosing alternative 2 instead of alternative 4. The time perspective is considered in SCORE in the discounting in the CBA, but the time uncertainties are not explicitly handled.

Moreover, among the factors that could influence the decision-making process, it has to be considered that in-situ techniques might overall be associated with more uncertainties and risk to delays than excavation, as already mentioned. The applicability and effectiveness of in-situ techniques depend on the type of soil and geomorphologic conditions and other characteristics that might be present below the ground level and that may have been overlooked in risk assessment analyses (Gomes, et al., 2013; Kuppusamy, et al., 2016). Also, it is generally more difficult to monitor the effectiveness of in-situ techniques than classic excavation (Kuppusamy, et al., 2016). Therefore, the decision-maker(s) might prefer alternatives that are not among the ones that scored the highest in the analysis, but that give less uncertainties in regard to practical applications.

## 7.8. Some challenges in the SCORE method

Regarding the SCORE method itself, a problem was noticed in the results when assigning 'high' uncertainties in the sub-criteria of the economic domain. In SCORE, the value provided by the user in the economic section is the most probable value of the present value of all the cost and benefits items of each alternative, i.e. the mode of the uncertainty density function (Rosén, et al., 2015), shown in Figure 4 in Section 3. The NPV that SCORE gives as a result, however, is the mean value of the distribution after the simulation, therefore the deviation between the mode and the mean is larger the higher the standard deviation (and thus uncertainty) is. In a case like this project, where the remediation cost is high, the differences between the most likely values used as input in SCORE and the values given as a result by the model are substantial and may affect the overall assessment.

In this assessment, a 'medium' value of the uncertainties was given to the cost inputs of alternatives 2 to 5, even if in reality the uncertainty for alternative 3, 4 and (especially) 5 might be considered high. However, this would not necessarily correspond to how 'high' uncertainty presently is defined in SCORE. A simulation with 'high' uncertainty assigned to the cost of alternatives 3, 4 and 5 was run, and as it is shown in Appendix X (scenario z). The assigned uncertainties heavily influence the economic sustainability scores, where the NPVs of the alternatives with high uncertainties were much lower than in the previous scenarios. As a consequence, the total sustainability score was influenced by the new scores in the economic domain, lowering the scores of the above-mentioned alternatives, but without changing the ranking. It was therefore assessed that assigning a medium uncertainty instead would have given results more reliable and close to the reality. It is currently discussed how this feature should be improved within the SCORE development team at Chalmers in order to be able to assign the proper uncertainty value without facing this problem.

# 8. Conclusion

The sustainability assessment carried out in this project allowed to reach various conclusions, in regard to the methods used and to the project itself:

- Sustainability assessment of remediation involves the need of information of very different characters, from site-specific data to environmental footprint analyses and economic analyses, as well as the need to take into account views and preferences of the involved stakeholders. The assessment will be as reliable as the input data are.

- The novelty of the study consisted in developing a new approach to include the assessment of in-situ techniques in the SCORE framework, and this was done elaborating further the environmental criteria in two ways. First, dividing the sub-criteria already present that describe the negative effect of the remediation on soil, groundwater and surface water in sub-subcriteria and scoring them semi-quantitatively using literature and case-studies to identify the secondary effects of the studied technologies. Then, scoring quantitatively the criteria describing the negative impacts of the remediation on air, use of non-renewable natural resources and generation of non-recyclable waste, dividing the first two criteria in sub-criteria chosen from the outputs of a streamlined LCA, and quantifying the amount of waste produced to score the latter.

- The suggested approach to the assessment of secondary environmental effects of both ex-situ and in-situ techniques developed in the project was successfully applied in the SCORE analysis of the case-study site. However, more applications are needed in order to further improve it.

- Due to intrinsic difficulties of the real site and data scarcity, the assessment was based on a conceptualized site and this has to be kept in mind to use the results in the decision-making process at the real site. In fact, the complex geology often present in real sites might change the way the different alternatives would be implemented on-site, and even their applicability. Moreover, if the assumptions on meeting the clean-up goals for all the alternatives and on the time needed for the remediation would not prove correct at the real site, the result of the SCORE analysis might change. Nevertheless, the methodology used can be applied to the real site, when data is more reliable.

- The alternatives that obtained the highest scores in all the scenarios are alt.2 (excavation of 1 meter of soil, solidification/stabilization with a lime/cement/persulfate mix from 1 to 5 meters b.g.l. and ISCO with persulfate from 5 to 13 meters) and alt.4 (excavation of 1 meter of soil, solidification/stabilization with a lime/cement/persulfate mix from 1 to 5 meters b.g.l. and bioremediation with ORC solution from 5 to 13 meters b.g.l.).

- The results show that the remediation techniques involving lower amount of soil excavated and landfilled score better than the techniques involving extensive excavation and landfilling. Although this analysis is made under the assumption is that the in-situ techniques manages to reduce risk as effectively as the excavation techniques, this strengthen the idea that in-situ techniques should be used more often in remediation projects to the detriment of the classic excavation and disposal of contaminated soil in landfills.

- Other characteristics of the project may play a role in selecting the most suitable alternative(s) in a remediation project, amongst other eventual budget or time limits that cannot be exceeded. In light of this, alternative 2 might result as the best option in this project, due to the minor costs involved and, especially, due to the minor time-frame needed for the remediation (9-12 months versus 24-36 months).

- The challenge of assigning ‘high’ uncertainties to the economic criteria has been identified while working with SCORE, therefore further improvements of the method together with the reasoning on how to implement efficiently new features such as LCA and a way to include the time needed for remediation in the assessment should be studied, in order to develop this method further.

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# Appendices

## Appendix I – Results from Pilot Tests

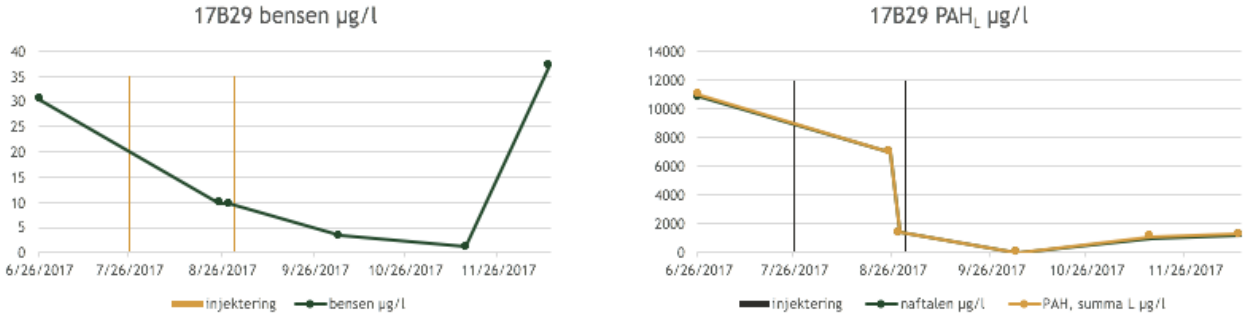


*Figure A 1. Results from ISCO with PersulfOx pilot test. In the graph on the left, according to the project leader, the high value at the end is believed to be due to contaminated water infiltration in the probe.*

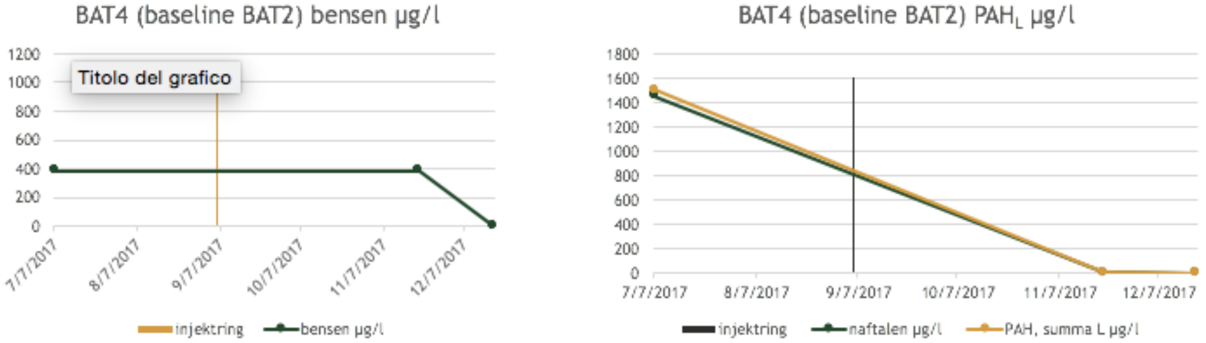


*Figure A 2. Results from the bioremediation with ORC solution pilot test.*

## Appendix II – Data for the Transport Scenarios

All the data are provided by Ecoloop.

- **Scenario I, II and IIIa: Truck (10km) + Boat (200km)**

Bulk ship with 3500 tons capacity, and 20 km/h average speed. Time needed to load the ship is one day, time to unload the ship is one day as well. Considering distance and time to load/unload, the ship is needed 2*200km/480km/h+48h=68 hours each time.
Price for land transport is 2SEK/ton/km, sea transport 20SEK/ton/day and load/unloading is 10 SEK/tonne.
Total price: 86.7 SEK/ton

- **Scenario I, II and IIIb: Truck (40km)**

Lorry of 7.5-16 metric ton of capacity, EURO 4 (option from SimaPro). Price of land transport: 2SEK/ton/km, cost of congestion traffic in Stockholm: 31 SEK/ton. Total price: 111 SEK/ton.

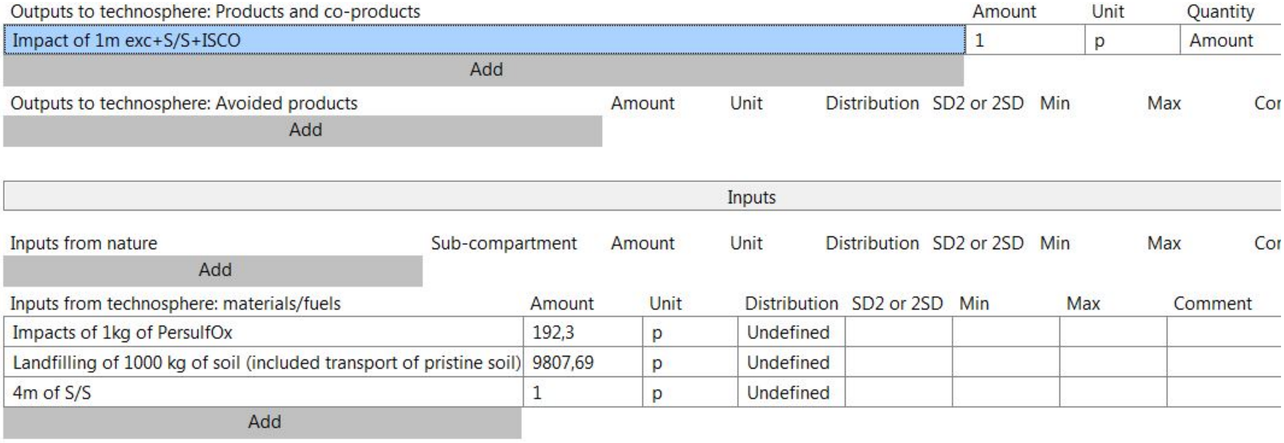
# Appendix III – SimaPro

- **Alternative 1**

SimaPro modelling of alternative 1 is shown in Figure 11, 12, 13, 14, 15.

- **Alternative 2**

Part of the modelling is shown in Figure 11, 12, 13 and 14. Landfilling is modelled as shown in Figure 15, but with different amount of soil.



| Outputs to technosphere: Products and co-products | Amount | Unit | Quantity |
|---|---|---|---|
| Impact of 1m exc+S/S+ISCO | 1 | p | Amount |

Outputs to technosphere: Avoided products

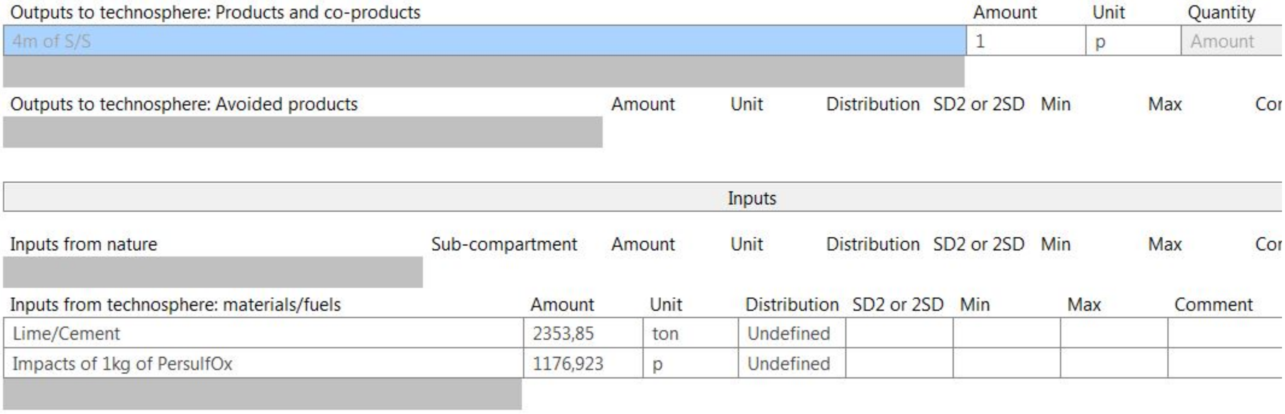
Inputs

Inputs from nature

| Inputs from technosphere: materials/fuels | Amount | Unit | Distribution | SD2 or 2SD | Min | Max | Comment |
|---|---|---|---|---|---|---|---|
| Impacts of 1kg of PersulfOx | 192,3 | p | Undefined | | | | |
| Landfilling of 1000 kg of soil (included transport of pristine soil) | 9807,69 | p | Undefined | | | | |
| 4m of S/S | 1 | p | Undefined | | | | |

*Figure A 3. SimaPro processes for alternative 2.*

Impacts of the S/S are shown below.



| Outputs to technosphere: Products and co-products | Amount | Unit | Quantity |
|---|---|---|---|
| 4m of S/S | 1 | p | Amount |

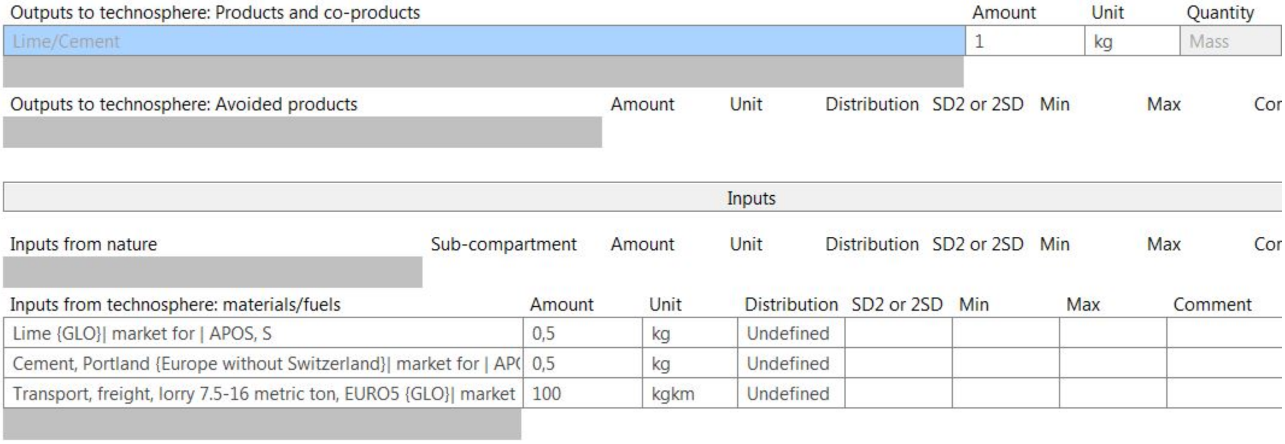
Outputs to technosphere: Avoided products

Inputs

Inputs from nature

| Inputs from technosphere: materials/fuels | Amount | Unit | Distribution | SD2 or 2SD | Min | Max | Comment |
|---|---|---|---|---|---|---|---|
| Lime/Cement | 2353,85 | ton | Undefined | | | | |
| Impacts of 1kg of PersulfOx | 1176,923 | p | Undefined | | | | |

*Figure A 4. SimaPro modelling for S/S. Impacts of PersulfOx are used because in S/S persulfate is used as well.*



| Outputs to technosphere: Products and co-products | Amount | Unit | Quantity |
|---|---|---|---|
| Lime/Cement | 1 | kg | Mass |

Outputs to technosphere: Avoided products

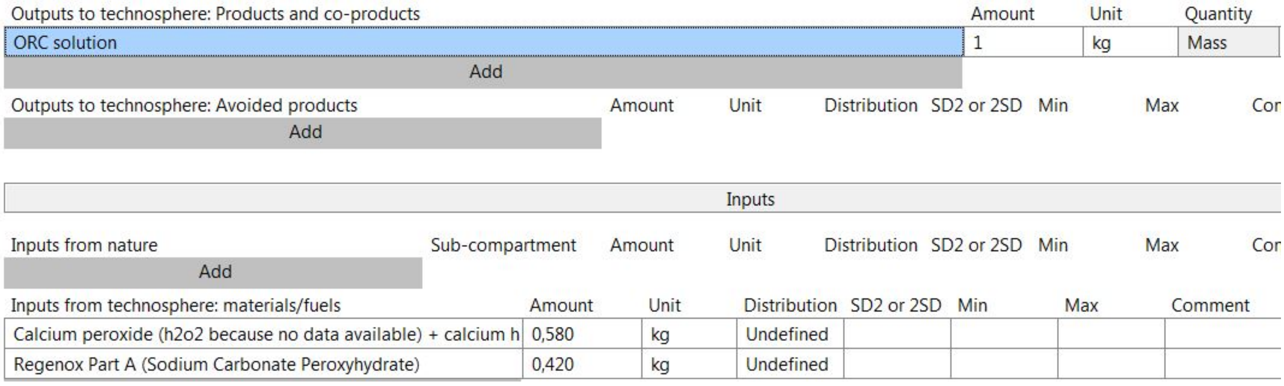
Inputs

Inputs from nature

| Inputs from technosphere: materials/fuels | Amount | Unit | Distribution | SD2 or 2SD | Min | Max | Comment |
|---|---|---|---|---|---|---|---|
| Lime {GLO}\| market for \| APOS, S | 0,5 | kg | Undefined | | | | |
| Cement, Portland {Europe without Switzerland}\| market for \| AP( | 0,5 | kg | Undefined | | | | |
| Transport, freight, lorry 7.5-16 metric ton, EURO5 {GLO}\| market | 100 | kgkm | Undefined | | | | |

*Figure A 5. SimaPro modelling of lime/cement mixture.*

## Alternative 3



| Outputs to technosphere: Products and co-products | Amount | Unit | Quantity |
|---|---|---|---|
| ORC solution | 1 | kg | Mass |

Add

| Outputs to technosphere: Avoided products | Amount | Unit | Distribution | SD2 or 2SD | Min | Max | Cor |
|---|---|---|---|---|---|---|---|

Add

Inputs

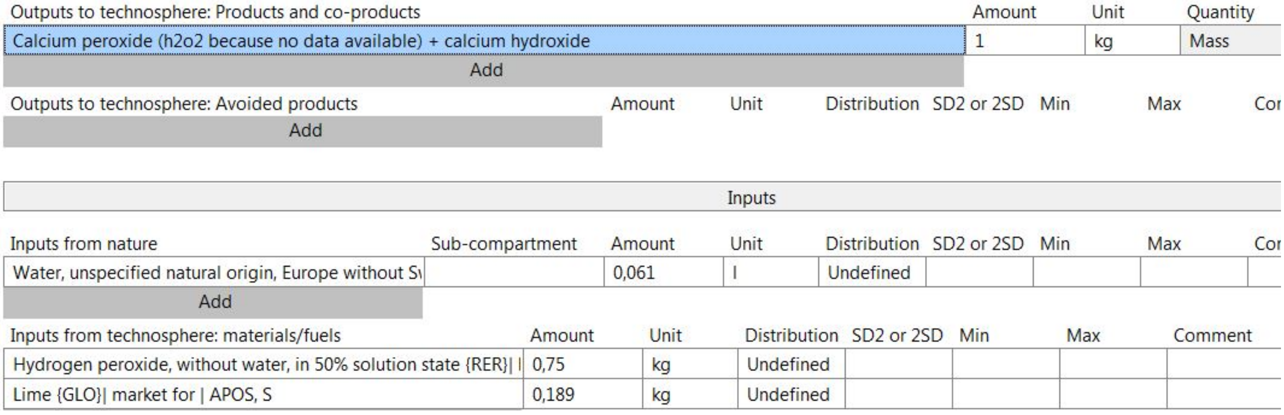
| Inputs from nature | Sub-compartment | Amount | Unit | Distribution | SD2 or 2SD | Min | Max | Cor |
|---|---|---|---|---|---|---|---|---|

Add

| Inputs from technosphere: materials/fuels | Amount | Unit | Distribution | SD2 or 2SD | Min | Max | Comment |
|---|---|---|---|---|---|---|---|
| Calcium peroxide (h2o2 because no data available) + calcium h | 0,580 | kg | Undefined | | | | |
| Regenox Part A (Sodium Carbonate Peroxyhydrate) | 0,420 | kg | Undefined | | | | |

*Figure A 6. Composition of ORC solution.*

The chemicals composing ORC solution were modelled as shown below.



| Outputs to technosphere: Products and co-products | Amount | Unit | Quantity |
|---|---|---|---|
| Calcium peroxide (h2o2 because no data available) + calcium hydroxide | 1 | kg | Mass |

Add

| Outputs to technosphere: Avoided products | Amount | Unit | Distribution | SD2 or 2SD | Min | Max | Cor |
|---|---|---|---|---|---|---|---|

Add

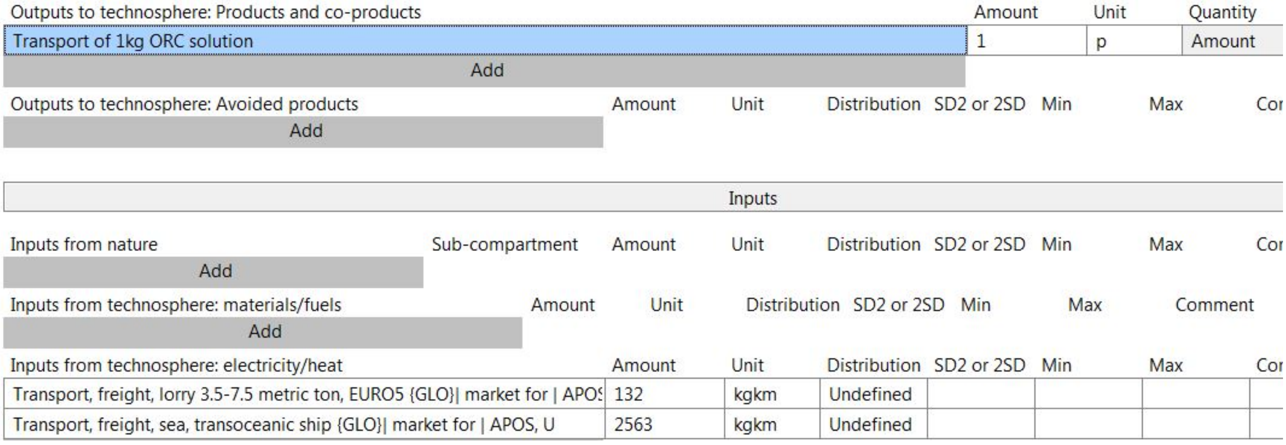
Inputs

| Inputs from nature | Sub-compartment | Amount | Unit | Distribution | SD2 or 2SD | Min | Max | Cor |
|---|---|---|---|---|---|---|---|---|
| Water, unspecified natural origin, Europe without S | | 0,061 | l | Undefined | | | | |

Add

| Inputs from technosphere: materials/fuels | Amount | Unit | Distribution | SD2 or 2SD | Min | Max | Comment |
|---|---|---|---|---|---|---|---|
| Hydrogen peroxide, without water, in 50% solution state {RER}\| I | 0,75 | kg | Undefined | | | | |
| Lime {GLO}\| market for \| APOS, S | 0,189 | kg | Undefined | | | | |

*Figure A 7. Composition of the calcium peroxide (assumed as hydrogen peroxyde) + calcium hydroxide (lime + water) part.*



| Outputs to technosphere: Products and co-products | Amount | Unit | Quantity |
|---|---|---|---|
| Transport of 1kg ORC solution | 1 | p | Amount |

Add

| Outputs to technosphere: Avoided products | Amount | Unit | Distribution | SD2 or 2SD | Min | Max | Cor |
|---|---|---|---|---|---|---|---|

Add

Inputs

| Inputs from nature | Sub-compartment | Amount | Unit | Distribution | SD2 or 2SD | Min | Max | Cor |
|---|---|---|---|---|---|---|---|---|

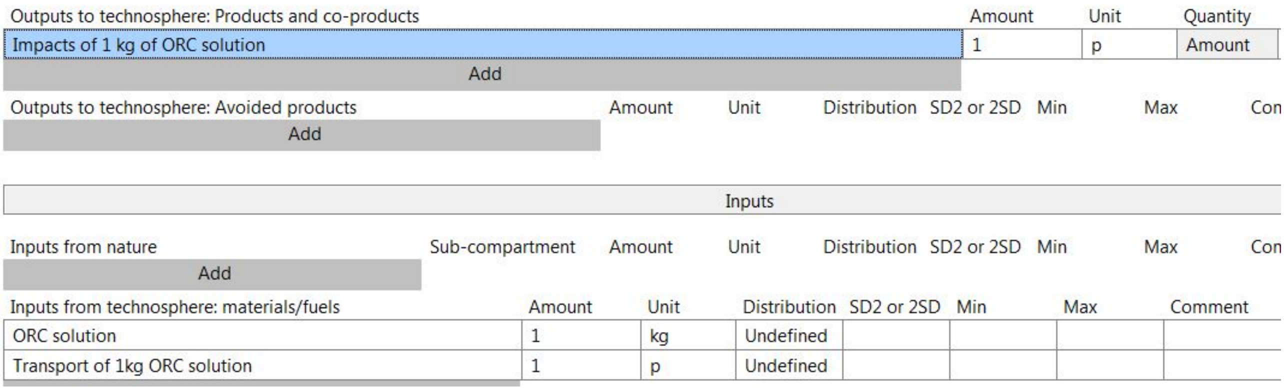
Add

| Inputs from technosphere: materials/fuels | Amount | Unit | Distribution | SD2 or 2SD | Min | Max | Comment |
|---|---|---|---|---|---|---|---|

Add

| Inputs from technosphere: electricity/heat | Amount | Unit | Distribution | SD2 or 2SD | Min | Max | Cor |
|---|---|---|---|---|---|---|---|
| Transport, freight, lorry 3.5-7.5 metric ton, EURO5 {GLO}\| market for \| APO | 132 | kgkm | Undefined | | | | |
| Transport, freight, sea, transoceanic ship {GLO}\| market for \| APOS, U | 2563 | kgkm | Undefined | | | | |

*Figure A 8. Impacts of the transport of 1 kg of ORC solution.*



| Outputs to technosphere: Products and co-products | Amount | Unit | Quantity |
|---|---|---|---|
| Impacts of 1 kg of ORC solution | 1 | p | Amount |

| Outputs to technosphere: Avoided products | Amount | Unit | Distribution | SD2 or 2SD | Min | Max | Con |
|---|---|---|---|---|---|---|---|

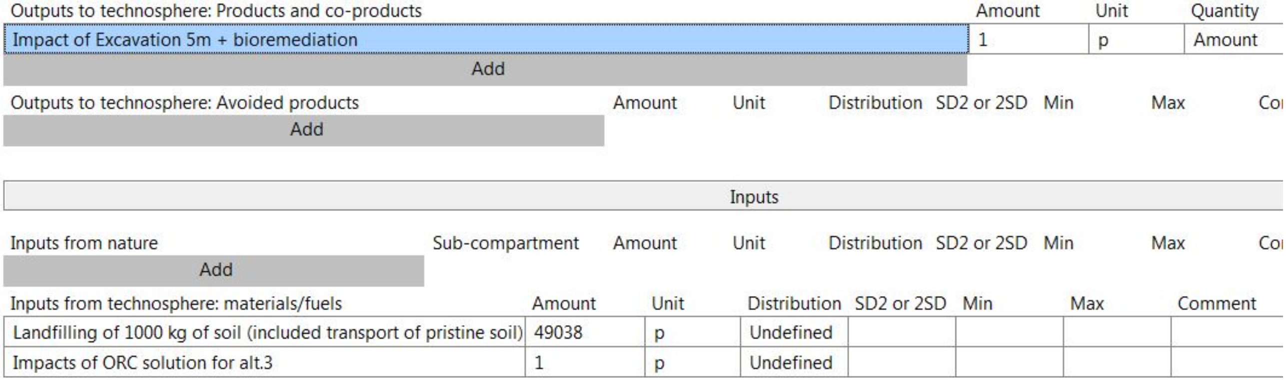
Inputs

| Inputs from nature | Sub-compartment | Amount | Unit | Distribution | SD2 or 2SD | Min | Max | Con |
|---|---|---|---|---|---|---|---|---|

| Inputs from technosphere: materials/fuels | Amount | Unit | Distribution | SD2 or 2SD | Min | Max | Comment |
|---|---|---|---|---|---|---|---|
| ORC solution | 1 | kg | Undefined | | | | |
| Transport of 1kg ORC solution | 1 | p | Undefined | | | | |

*Figure A 9. Total impacts of ORC solution.*

The total impacts for Alternative 3 are modelled from the impacts shown above scaled to the amount of ORC solution used plus the impacts of dig&dump, as shown below.



| Outputs to technosphere: Products and co-products | Amount | Unit | Quantity |
|---|---|---|---|
| Impact of Excavation 5m + bioremediation | 1 | p | Amount |

| Outputs to technosphere: Avoided products | Amount | Unit | Distribution | SD2 or 2SD | Min | Max | Co |
|---|---|---|---|---|---|---|---|

Inputs

| Inputs from nature | Sub-compartment | Amount | Unit | Distribution | SD2 or 2SD | Min | Max | Co |
|---|---|---|---|---|---|---|---|---|

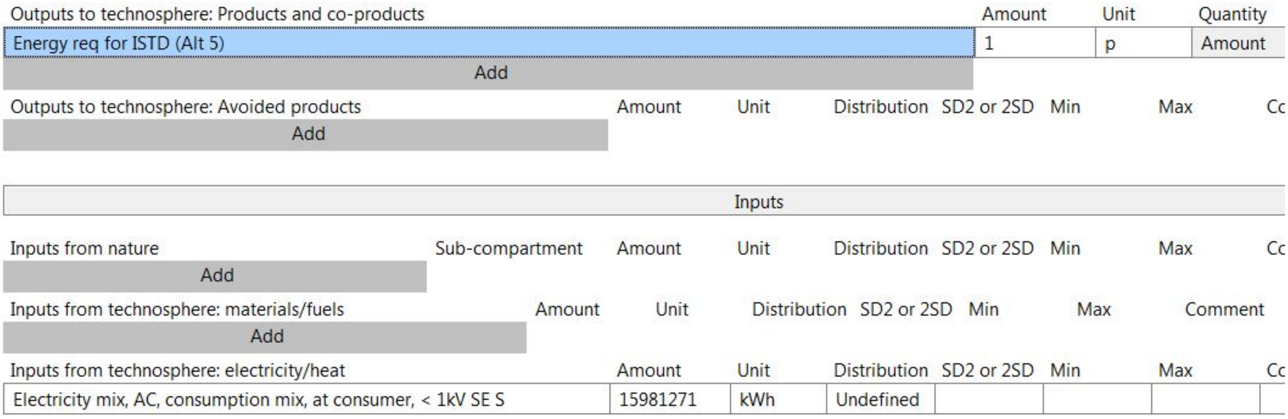
| Inputs from technosphere: materials/fuels | Amount | Unit | Distribution | SD2 or 2SD | Min | Max | Comment |
|---|---|---|---|---|---|---|---|
| Landfilling of 1000 kg of soil (included transport of pristine soil) | 49038 | p | Undefined | | | | |
| Impacts of ORC solution for alt.3 | 1 | p | Undefined | | | | |

*Figure A 10. Impacts of alternative 4.*

### Alternative 4

The processes modelled in SimaPro for alternative 4 are the same as for alternative 2 (with bioremediation instead of ISCO) and alternative 3, with less material excavated and landfilled.

### Alternative 5



| Outputs to technosphere: Products and co-products | Amount | Unit | Quantity |
|---|---|---|---|
| Energy req for ISTD (Alt 5) | 1 | p | Amount |

| Outputs to technosphere: Avoided products | Amount | Unit | Distribution | SD2 or 2SD | Min | Max | Cc |
|---|---|---|---|---|---|---|---|

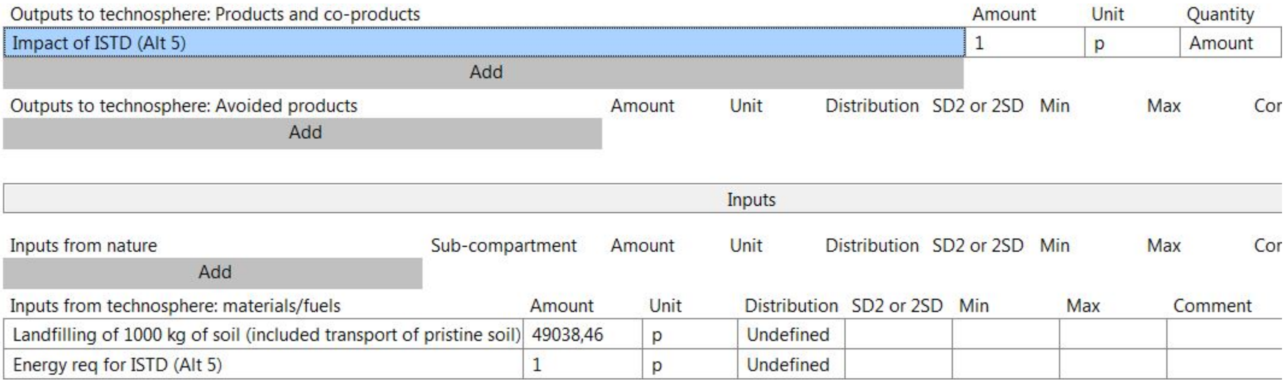
Inputs

| Inputs from nature | Sub-compartment | Amount | Unit | Distribution | SD2 or 2SD | Min | Max | Cc |
|---|---|---|---|---|---|---|---|---|

| Inputs from technosphere: materials/fuels | Amount | Unit | Distribution | SD2 or 2SD | Min | Max | Comment |
|---|---|---|---|---|---|---|---|

| Inputs from technosphere: electricity/heat | Amount | Unit | Distribution | SD2 or 2SD | Min | Max | Cc |
|---|---|---|---|---|---|---|---|
| Electricity mix, AC, consumption mix, at consumer, < 1kV SE S | 15981271 | kWh | Undefined | | | | |

Figure A 11. Energy requirements for alternative 5 in SimaPro.



| Outputs to technosphere: Products and co-products | Amount | Unit | Quantity |
|---|---|---|---|
| Impact of ISTD (Alt 5) | 1 | p | Amount |

| Outputs to technosphere: Avoided products | Amount | Unit | Distribution | SD2 or 2SD | Min | Max | Cor |
|---|---|---|---|---|---|---|---|

| Inputs from nature | Sub-compartment | Amount | Unit | Distribution | SD2 or 2SD | Min | Max | Cor |
|---|---|---|---|---|---|---|---|---|

| Inputs from technosphere: materials/fuels | Amount | Unit | Distribution | SD2 or 2SD | Min | Max | Comment |
|---|---|---|---|---|---|---|---|
| Landfilling of 1000 kg of soil (included transport of pristine soil) | 49038,46 | p | Undefined | | | | |
| Energy req for ISTD (Alt 5) | 1 | p | Undefined | | | | |

*Figure A 12. Modelling of alternative 5 impacts in SimaPro.*

**Scenario with transport by truck (10km) + transport by boat (200km)**

*Results for the Selected Categories*

Comparison method used was ReCiPe 2016 Midpoint (H) V1.01

*Table A 1. SimaPro results for the selected categories.*

| Impact category | Unit | Alt.1 | Alt.2 | Alt.3 | Alt.4 | Alt.5 |
|---|---|---|---|---|---|---|
| Global warming | kg CO2 eq | 1,30E+06 | 1,41E+06 | 1,30E+06 | 1,43E+06 | 3,08E+06 |
| Ozone formation, Human health | kg NOx eq | 8,62E+03 | 3,66E+03 | 8,55E+03 | 3,70E+03 | 8,53E+03 |
| Fine particulate matter formation | kg PM2.5 eq | 1,71E+03 | 1,05E+03 | 1,69E+03 | 1,08E+03 | 2,44E+03 |
| Terrestrial acidification | kg SO2 eq | 4,61E+03 | 2,77E+03 | 4,56E+03 | 2,85E+03 | 7,03E+03 |
| Fossil resource scarcity | kg oil eq | 4,21E+05 | 2,06E+05 | 4,21E+05 | 2,13E+05 | 6,26E+05 |
| Water consumption | m3 | 2,58E+03 | 4,50E+03 | 3,60E+03 | 5,57E+03 | 1,82E+04 |

The values were normalized dividing the results in each impact category by the highest value in the category itself, in order to use them in Web-HIPRE.

*Table A 2. Results from SimaPro, normalized.*

| Impact category | Alt.1 | Alt.2 | Alt.3 | Alt.4 | Alt.5 |
|---|---|---|---|---|---|
| Global warming | 0,42 | 0,46 | 0,42 | 0,46 | 1,00 |
| Ozone formation, Human health | 1,00 | 0,42 | 0,99 | 0,43 | 0,99 |
| Fine particulate matter formation | 0,70 | 0,43 | 0,69 | 0,44 | 1,00 |
| Terrestrial acidification | 0,66 | 0,39 | 0,65 | 0,41 | 1,00 |
| Fossil resource scarcity | 0,67 | 0,33 | 0,67 | 0,34 | 1,00 |
| Water consumption | 0,14 | 0,25 | 0,20 | 0,31 | 1,00 |

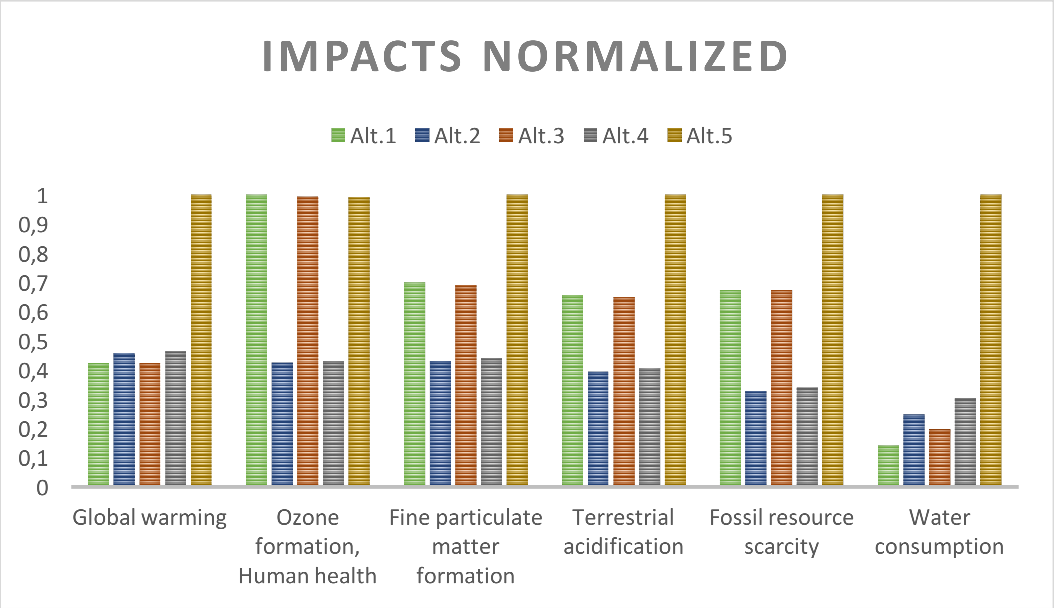


*Figure A 13. Results from SimaPro, normalized.*

The value shown in the normalized table were then used in Web-HIPRE.

*Results for the Alternatives in all the Categories*

Comparison method used was ReCiPe 2016 Midpoint (H) V1.01

*Table A 3. SimaPro results in all the categories.*

| **Impact category** | **Unit** | **Alt.1** | **Alt.2** | **Alt.3** | **Alt.4** | **Alt.5** |
|---|---|---|---|---|---|---|
| Global warming | kg CO2 eq | 1,30E+06 | 1,41E+06 | 1,30E+06 | 1,43E+06 | 3,08E+06 |
| Stratospheric ozone depletion | kg CFC11 eq | 6,27E-01 | 2,73E-01 | 6,23E-01 | 2,80E-01 | 2,86E+00 |
| Ionizing radiation | kBq Co-60 eq | 1,73E+04 | 3,50E+04 | 1,91E+04 | 3,73E+04 | 1,81E+06 |
| Ozone formation, Human health | kg NOx eq | 8,62E+03 | 3,66E+03 | 8,55E+03 | 3,70E+03 | 8,53E+03 |
| Fine particulate matter formation | kg PM2.5 eq | 1,71E+03 | 1,05E+03 | 1,69E+03 | 1,08E+03 | 2,44E+03 |
| Ozone formation, Terrestrial ecosystems | kg NOx eq | 8,71E+03 | 3,70E+03 | 8,64E+03 | 3,74E+03 | 8,64E+03 |
| Terrestrial acidification | kg SO2 eq | 4,61E+03 | 2,77E+03 | 4,56E+03 | 2,85E+03 | 7,03E+03 |
| Freshwater eutrophication | kg P eq | 7,31E+01 | 1,25E+02 | 7,86E+01 | 1,32E+02 | 7,15E+01 |
| Marine eutrophication | kg N eq | 6,27E+00 | 8,92E+00 | 6,85E+00 | 9,64E+00 | 2,33E+01 |
| Terrestrial ecotoxicity | kg 1,4-DCB | 8,59E+06 | 3,11E+06 | 8,54E+06 | 3,18E+06 | 8,84E+06 |
| Freshwater ecotoxicity | kg 1,4-DCB | 1,43E+04 | 9,93E+03 | 1,49E+04 | 1,08E+04 | 1,44E+04 |
| Marine ecotoxicity | kg 1,4-DCB | 2,43E+04 | 1,52E+04 | 2,51E+04 | 1,65E+04 | 2,47E+04 |
| Human carcinogenic toxicity | kg 1,4-DCB | 2,20E+04 | 1,62E+04 | 2,38E+04 | 1,84E+04 | 2,18E+04 |
| Human non-carcinogenic toxicity | kg 1,4-DCB | 5,71E+05 | 3,35E+05 | 5,84E+05 | 3,59E+05 | 5,76E+05 |
| Land use | m2a crop eq | 2,84E+04 | 1,48E+04 | 2,86E+04 | 1,53E+04 | 2,80E+04 |
| Mineral resource scarcity | kg Cu eq | 1,85E+03 | 6,14E+03 | 1,88E+03 | 6,21E+03 | 1,99E+03 |
| Fossil resource scarcity | kg oil eq | 4,21E+05 | 2,06E+05 | 4,21E+05 | 2,13E+05 | 6,26E+05 |
| Water consumption | m3 | 2,58E+03 | 4,50E+03 | 3,60E+03 | 5,57E+03 | 1,82E+04 |

- **Scenario with Transport by Truck (40km)**

*Results for the Selected Categories*

Comparison method used was ReCiPe 2016 Midpoint (H) V1.01

*Table A 4. SimaPro results for the selected categories.*

| Impact category | Unit | Alt.1 | Alt.2 | Alt.3 | Alt.4 | Alt.5 |
|---|---|---|---|---|---|---|
| Global warming | kg CO2 eq | 1,34E+06 | 1,42E+06 | 1,34E+06 | 1,44E+06 | 3,12E+06 |
| Ozone formation, Human health | kg NOx eq | 4,73E+03 | 2,88E+03 | 4,66E+03 | 2,92E+03 | 4,65E+03 |
| Fine particulate matter formation | kg PM2.5 eq | 1,56E+03 | 1,02E+03 | 1,55E+03 | 1,05E+03 | 2,30E+03 |
| Terrestrial acidification | kg SO2 eq | 3,66E+03 | 2,58E+03 | 3,62E+03 | 2,66E+03 | 6,08E+03 |
| Fossil resource scarcity | kg oil eq | 4,47E+05 | 2,12E+05 | 4,47E+05 | 2,18E+05 | 6,52E+05 |
| Water consumption | m3 | 4,03E+03 | 4,79E+03 | 5,05E+03 | 5,86E+03 | 1,97E+04 |

The values were normalized dividing the results in each impact category by the highest value in the category itself, in order to use them in Web-HIPRE.

*Table A 5. Results from SimaPro, normalized.*

| Impact category | Alt.1 | Alt.2 | Alt.3 | Alt.4 | Alt.5 |
|---|---|---|---|---|---|
| Global warming | 0,43 | 0,46 | 0,43 | 0,46 | 1,00 |
| Ozone formation, Human health | 1,00 | 0,61 | 0,99 | 0,62 | 0,98 |
| Fine particulate matter formation | 0,68 | 0,44 | 0,67 | 0,46 | 1,00 |
| Terrestrial acidification | 0,60 | 0,42 | 0,59 | 0,44 | 1,00 |
| Fossil resource scarcity | 0,69 | 0,32 | 0,69 | 0,33 | 1,00 |
| Water consumption | 0,21 | 0,24 | 0,26 | 0,30 | 1,00 |

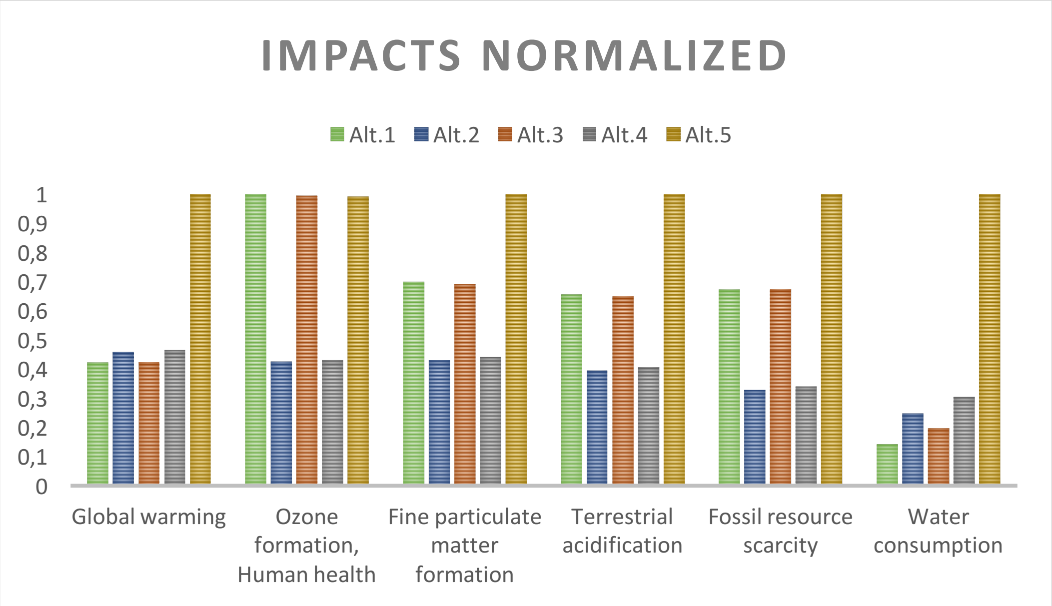


*Figure A 14. Results from SimaPro, normalized.*

The value shown in the normalized table were then used in Web-HIPRE.

*Results for the Alternatives in all the Categories*

Comparison method used was ReCiPe 2016 Midpoint (H) V1.01

*Table A 6. SimaPro results in all the categories.*

| Impact category | Unit | Alt.1 | Alt.2 | Alt.3 | Alt.4 | Alt.5 |
|---|---|---|---|---|---|---|
| Global warming | kg CO2 eq | 1,34E+06 | 1,42E+06 | 1,34E+06 | 1,44E+06 | 3,12E+06 |
| Stratospheric ozone depletion | kg CFC11 eq | 8,46E-01 | 3,16E-01 | 8,42E-01 | 3,24E-01 | 3,08E+00 |
| Ionizing radiation | kBq Co-60 eq | 2,66E+04 | 3,69E+04 | 2,84E+04 | 3,92E+04 | 1,82E+06 |
| Ozone formation, Human health | kg NOx eq | 4,73E+03 | 2,88E+03 | 4,66E+03 | 2,92E+03 | 4,65E+03 |
| Fine particulate matter formation | kg PM2.5 eq | 1,56E+03 | 1,02E+03 | 1,55E+03 | 1,05E+03 | 2,30E+03 |
| Ozone formation, Terrestrial ecosystems | kg NOx eq | 4,84E+03 | 2,93E+03 | 4,77E+03 | 2,97E+03 | 4,77E+03 |
| Terrestrial acidification | kg SO2 eq | 3,66E+03 | 2,58E+03 | 3,62E+03 | 2,66E+03 | 6,08E+03 |
| Freshwater eutrophication | kg P eq | 1,16E+02 | 1,33E+02 | 1,21E+02 | 1,41E+02 | 1,14E+02 |
| Marine eutrophication | kg N eq | 9,03E+00 | 9,47E+00 | 9,61E+00 | 1,02E+01 | 2,61E+01 |
| Terrestrial ecotoxicity | kg 1,4-DCB | 1,38E+07 | 4,14E+06 | 1,37E+07 | 4,22E+06 | 1,40E+07 |
| Freshwater ecotoxicity | kg 1,4-DCB | 2,29E+04 | 1,16E+04 | 2,35E+04 | 1,26E+04 | 2,30E+04 |
| Marine ecotoxicity | kg 1,4-DCB | 3,83E+04 | 1,80E+04 | 3,91E+04 | 1,93E+04 | 3,87E+04 |
| Human carcinogenic toxicity | kg 1,4-DCB | 3,30E+04 | 1,83E+04 | 3,47E+04 | 2,06E+04 | 3,28E+04 |
| Human non-carcinogenic toxicity | kg 1,4-DCB | 8,57E+05 | 3,92E+05 | 8,70E+05 | 4,16E+05 | 8,62E+05 |
| Land use | m2a crop eq | 4,58E+04 | 1,82E+04 | 4,59E+04 | 1,88E+04 | 4,54E+04 |
| Mineral resource scarcity | kg Cu eq | 2,91E+03 | 6,35E+03 | 2,94E+03 | 6,43E+03 | 3,05E+03 |
| Fossil resource scarcity | kg oil eq | 4,47E+05 | 2,12E+05 | 4,47E+05 | 2,18E+05 | 6,52E+05 |
| Water consumption | m3 | 4,03E+03 | 4,79E+03 | 5,05E+03 | 5,86E+03 | 1,97E+04 |

# Appendix IV – Web HIPRE

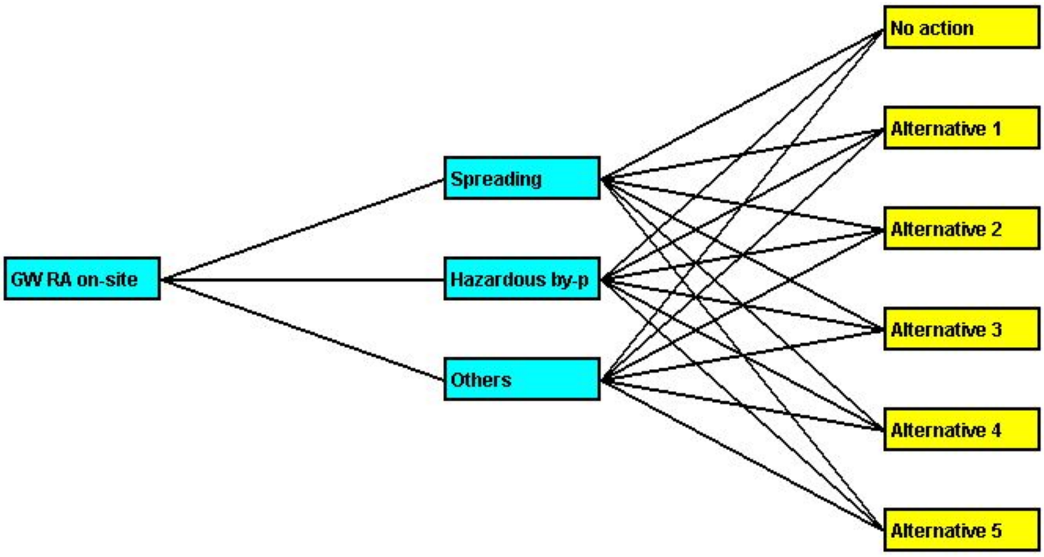


*Figure A 15. Web-HIPRE structure for E3 - Groundwater RA on-site.*

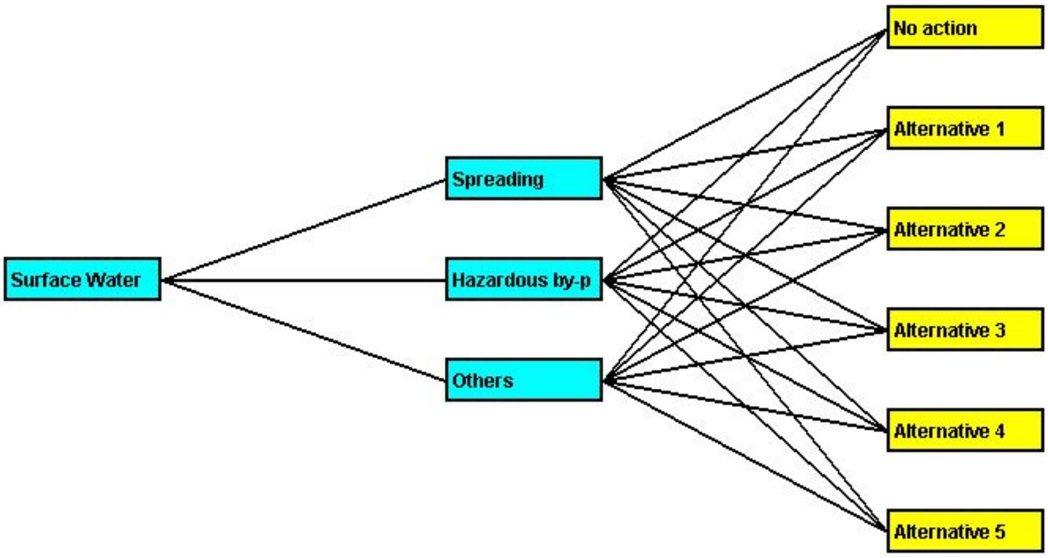


*Figure A 16. Web-HIPRE structure for E4 - surface water RA off-site.*

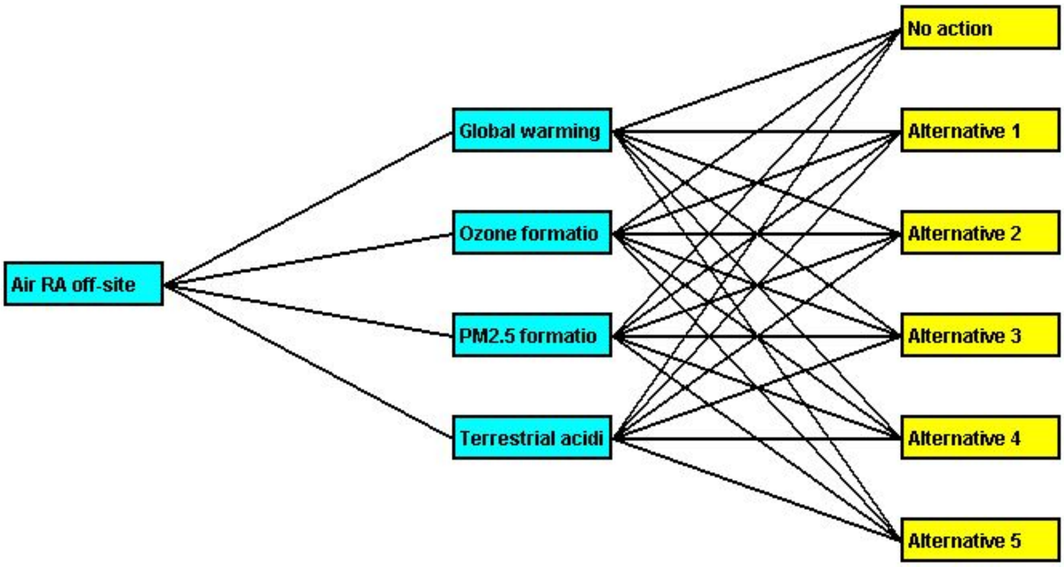


*Figure A 17. Web-HIPRE structure for E6 - Air RA off-site.*

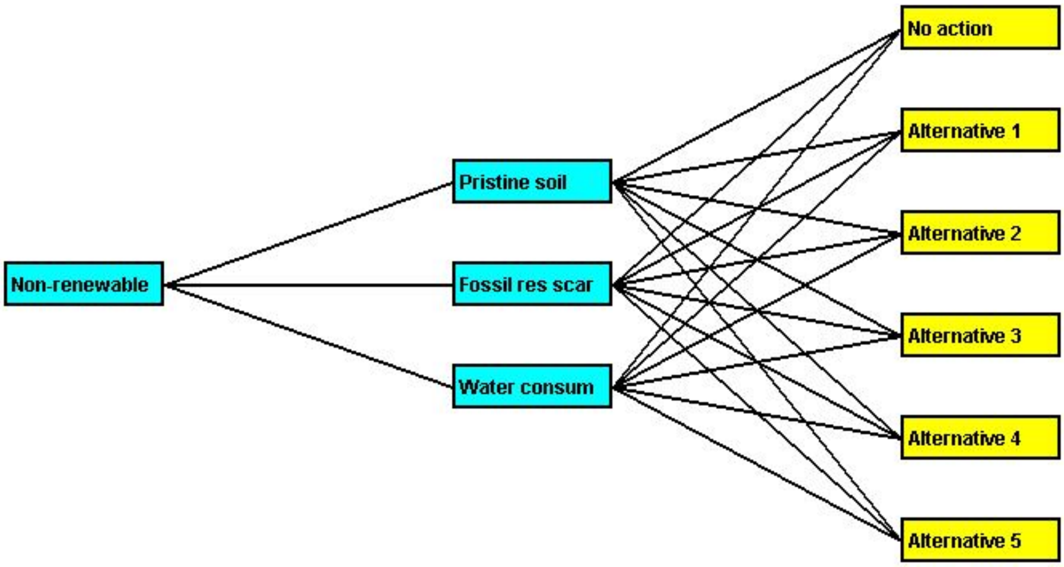
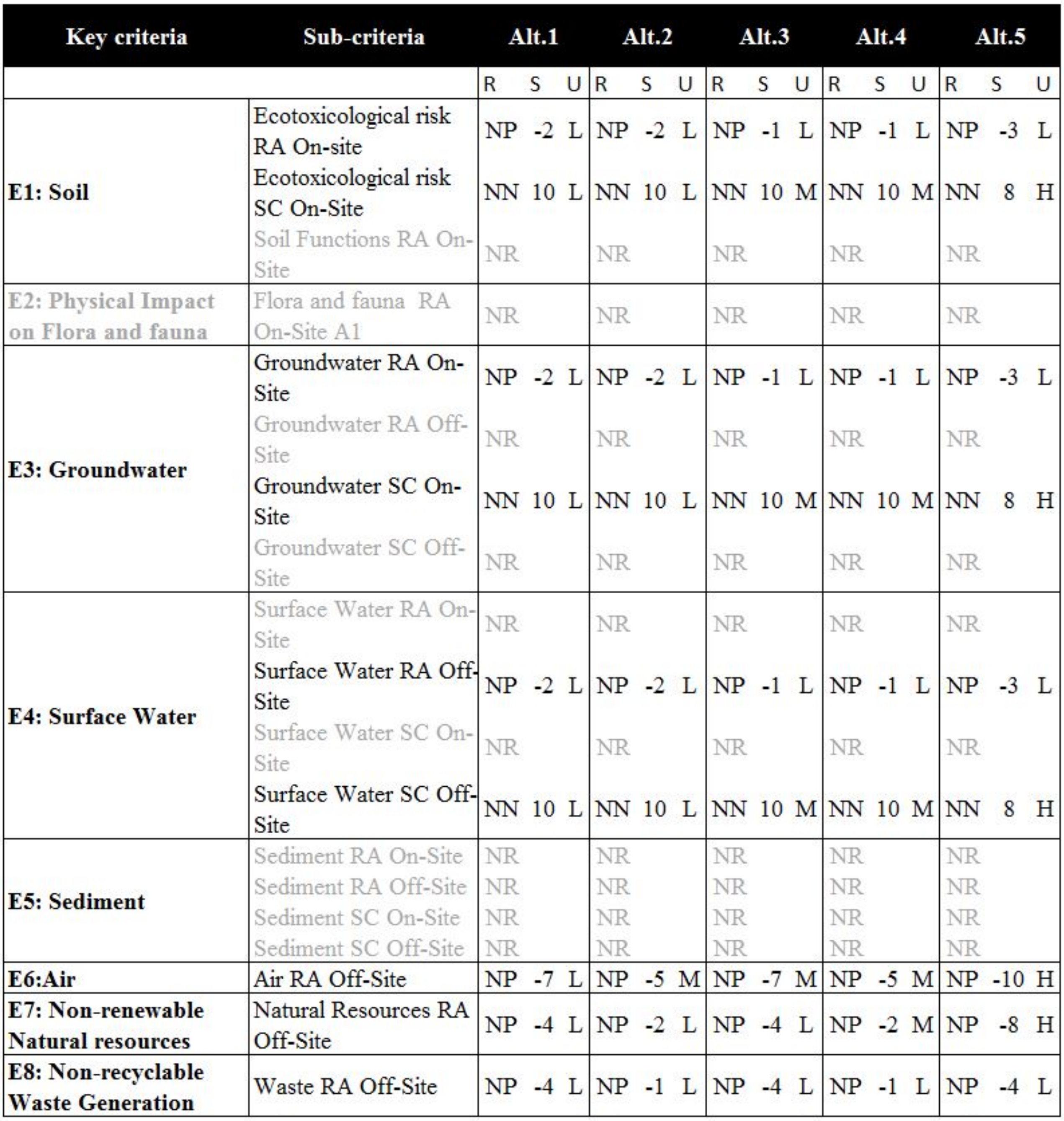


*Figure A 18. Web-HIPRE structure for E7 – Non-renewable natural resources.*

# Appendix V – Scoring of the Environmental Criteria

- **SCORE Inputs of Scenario I, II and III b**

*Table A 7. SCORE inputs of scenario I, II and III b.*

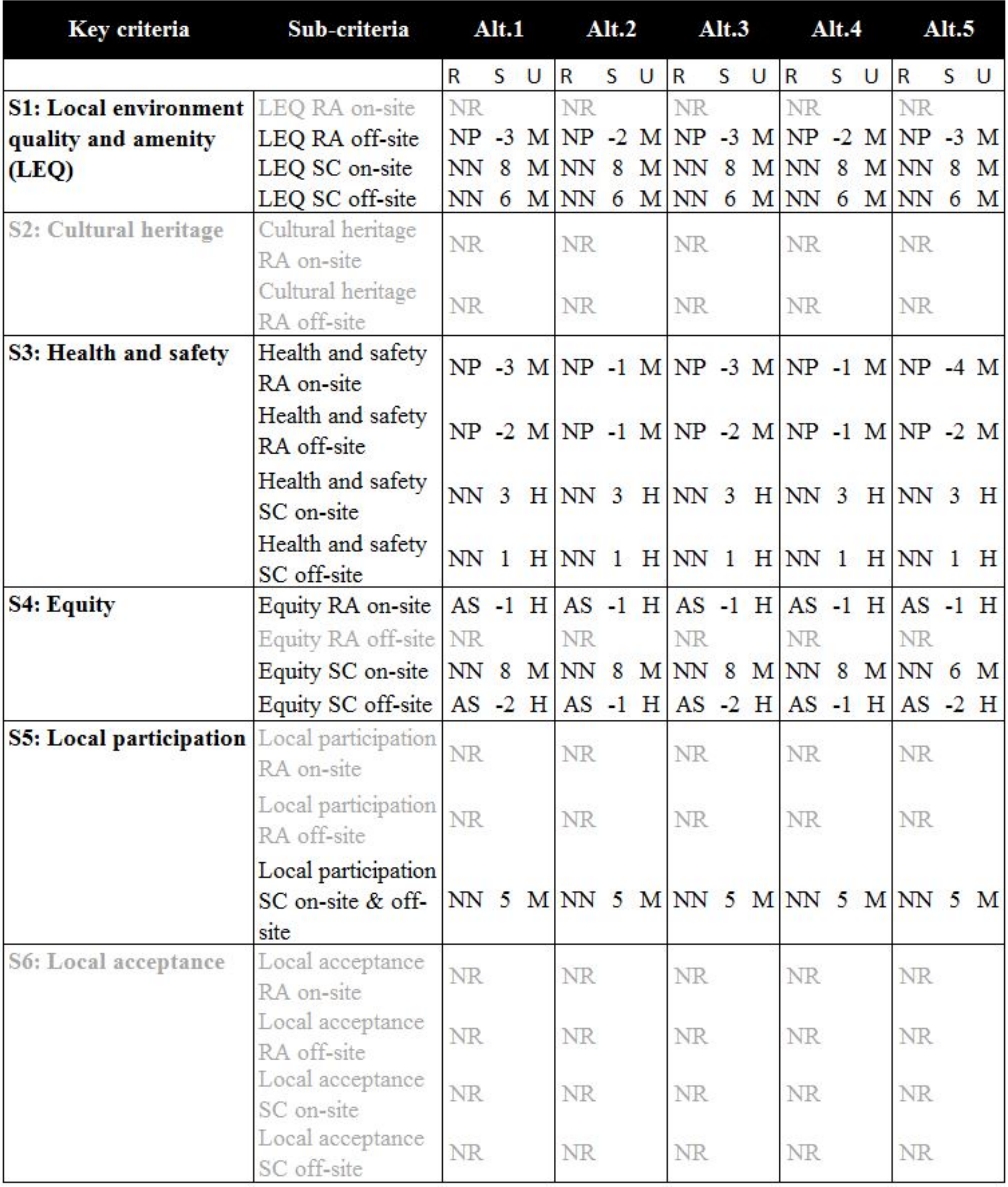


| Key criteria | Sub-criteria | Alt.1 | | | Alt.2 | | | Alt.3 | | | Alt.4 | | | Alt.5 | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | R | S | U | R | S | U | R | S | U | R | S | U | R | S | U |
| **E1: Soil** | Ecotoxicological risk RA On-site | NP | -2 | L | NP | -2 | L | NP | -1 | L | NP | -1 | L | NP | -3 | L |
| | Ecotoxicological risk SC On-Site | NN | 10 | L | NN | 10 | L | NN | 10 | M | NN | 10 | M | NN | 8 | H |
| | Soil Functions RA On-Site | NR | | | NR | | | NR | | | NR | | | NR | | |
| **E2: Physical Impact on Flora and fauna** | Flora and fauna RA On-Site A1 | NR | | | NR | | | NR | | | NR | | | NR | | |
| **E3: Groundwater** | Groundwater RA On-Site | NP | -2 | L | NP | -2 | L | NP | -1 | L | NP | -1 | L | NP | -3 | L |
| | Groundwater RA Off-Site | NR | | | NR | | | NR | | | NR | | | NR | | |
| | Groundwater SC On-Site | NN | 10 | L | NN | 10 | L | NN | 10 | M | NN | 10 | M | NN | 8 | H |
| | Groundwater SC Off-Site | NR | | | NR | | | NR | | | NR | | | NR | | |
| **E4: Surface Water** | Surface Water RA On-Site | NR | | | NR | | | NR | | | NR | | | NR | | |
| | Surface Water RA Off-Site | NP | -2 | L | NP | -2 | L | NP | -1 | L | NP | -1 | L | NP | -3 | L |
| | Surface Water SC On-Site | NR | | | NR | | | NR | | | NR | | | NR | | |
| | Surface Water SC Off-Site | NN | 10 | L | NN | 10 | L | NN | 10 | M | NN | 10 | M | NN | 8 | H |
| **E5: Sediment** | Sediment RA On-Site | NR | | | NR | | | NR | | | NR | | | NR | | |
| | Sediment RA Off-Site | NR | | | NR | | | NR | | | NR | | | NR | | |
| | Sediment SC On-Site | NR | | | NR | | | NR | | | NR | | | NR | | |
| | Sediment SC Off-Site | NR | | | NR | | | NR | | | NR | | | NR | | |
| **E6:Air** | Air RA Off-Site | NP | -7 | L | NP | -5 | M | NP | -7 | M | NP | -5 | M | NP | -10 | H |
| **E7: Non-renewable Natural resources** | Natural Resources RA Off-Site | NP | -4 | L | NP | -2 | L | NP | -4 | L | NP | -2 | M | NP | -8 | H |
| **E8: Non-recyclable Waste Generation** | Waste RA Off-Site | NP | -4 | L | NP | -1 | L | NP | -4 | L | NP | -1 | L | NP | -4 | L |

# Appendix VI – Scoring of the Social Criteria

- **SCORE Inputs of Scenario I, II and III b**

*Table A 8. SCORE inputs for scenario I, II and III b.*



| Key criteria | Sub-criteria | Alt.1 | | | Alt.2 | | | Alt.3 | | | Alt.4 | | | Alt.5 | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | R | S | U | R | S | U | R | S | U | R | S | U | R | S | U |
| **S1: Local environment quality and amenity (LEQ)** | LEQ RA on-site | NR | | | NR | | | NR | | | NR | | | NR | | |
| | LEQ RA off-site | NP | -3 | M | NP | -2 | M | NP | -3 | M | NP | -2 | M | NP | -3 | M |
| | LEQ SC on-site | NN | 8 | M | NN | 8 | M | NN | 8 | M | NN | 8 | M | NN | 8 | M |
| | LEQ SC off-site | NN | 6 | M | NN | 6 | M | NN | 6 | M | NN | 6 | M | NN | 6 | M |
| **S2: Cultural heritage** | Cultural heritage RA on-site | NR | | | NR | | | NR | | | NR | | | NR | | |
| | Cultural heritage RA off-site | NR | | | NR | | | NR | | | NR | | | NR | | |
| **S3: Health and safety** | Health and safety RA on-site | NP | -3 | M | NP | -1 | M | NP | -3 | M | NP | -1 | M | NP | -4 | M |
| | Health and safety RA off-site | NP | -2 | M | NP | -1 | M | NP | -2 | M | NP | -1 | M | NP | -2 | M |
| | Health and safety SC on-site | NN | 3 | H | NN | 3 | H | NN | 3 | H | NN | 3 | H | NN | 3 | H |
| | Health and safety SC off-site | NN | 1 | H | NN | 1 | H | NN | 1 | H | NN | 1 | H | NN | 1 | H |
| **S4: Equity** | Equity RA on-site | AS | -1 | H | AS | -1 | H | AS | -1 | H | AS | -1 | H | AS | -1 | H |
| | Equity RA off-site | NR | | | NR | | | NR | | | NR | | | NR | | |
| | Equity SC on-site | NN | 8 | M | NN | 8 | M | NN | 8 | M | NN | 8 | M | NN | 6 | M |
| | Equity SC off-site | AS | -2 | H | AS | -1 | H | AS | -2 | H | AS | -1 | H | AS | -2 | H |
| **S5: Local participation** | Local participation RA on-site | NR | | | NR | | | NR | | | NR | | | NR | | |
| | Local participation RA off-site | NR | | | NR | | | NR | | | NR | | | NR | | |
| | Local participation SC on-site & off-site | NN | 5 | M | NN | 5 | M | NN | 5 | M | NN | 5 | M | NN | 5 | M |
| **S6: Local acceptance** | Local acceptance RA on-site | NR | | | NR | | | NR | | | NR | | | NR | | |
| | Local acceptance RA off-site | NR | | | NR | | | NR | | | NR | | | NR | | |
| | Local acceptance SC on-site | NR | | | NR | | | NR | | | NR | | | NR | | |
| | Local acceptance SC off-site | NR | | | NR | | | NR | | | NR | | | NR | | |

# Appendix VII - Cost-Benefit Analysis

## Remediation costs

- *Alternative 1*

| Action | Unit | Alt. 1 | | |
|---|---|---|---|---|
| | | Mean | Min | Max |
| Excavation and sorting | MSEK | 3,61 | 2,88 | 4,33 |
| Environmental inspection (sampling, 2 persons) | MSEK | 2,63 | 2,25 | 3,00 |
| Environmental control (chemical analysis) | MSEK | 0,83 | 0,66 | 0,99 |
| Sheet piling | MSEK | 20,19 | 17,31 | 23,08 |
| Setting of storage areas and water treatment area | MSEK | 0,30 | 0,30 | 0,30 |
| Water purification including pumping and 'lowering' of GW | MSEK | 0,23 | 0,08 | 0,39 |
| Transport of contaminated soil (boat+truck) | MSEK | 4,25 | 4,25 | 4,25 |
| Transport of contaminated soil (truck) | MSEK | 5,44 | 5,44 | 5,44 |
| Landfilling of non-hazardous soil | MSEK | 8,46 | 4,66 | 12,26 |
| Landfilling of hazardous soil | MSEK | 8,54 | 5,15 | 11,93 |
| Landfilling of hazardous soil (including tar in free PAHe) | MSEK | 11,11 | 5,66 | 16,55 |
| Pristine soil (including transport and refill) | MSEK | 4,90 | 3,92 | 5,88 |
| ISCO (persulfate) (same price for soil and GW) | MSEK | 35,18 | 35,18 | 35,18 |
| S/S (total) | MSEK | 0,00 | 0,00 | 0,00 |
| ISTD | MSEK | 0,00 | 0,00 | 0,00 |
| Bioremediation | MSEK | 0,00 | 0,00 | 0,00 |
| Other costs (design, builder etc.) | MSEK | 10,57 | 8,77 | 12,36 |
| Unforeseen | MSEK | 15,85 | 13,16 | 18,54 |
| **Total Scenario 1a** | **MSEK** | **126,64** | **104,24** | **149,03** |
| **Total Scenario 1b** | **MSEK** | **127,83** | **105,44** | **150,22** |

- *Alternative 2*

| Action | Unit | Alt. 2 | | |
|---|---|---|---|---|
| | | Mean | Min | Max |
| Excavation and sorting | MSEK | 0,72 | 0,58 | 0,87 |
| Environmental inspection (sampling, 2 persons) | MSEK | 2,63 | 2,25 | 3,00 |
| Environmental control (chemical analysis) | MSEK | 0,83 | 0,66 | 0,99 |
| Sheet piling | MSEK | 20,19 | 17,31 | 23,08 |
| Setting of storage areas and water treatment area | MSEK | 0,30 | 0,30 | 0,30 |
| Water purification including pumping and 'lowering' of GW | MSEK | 0,00 | 0,00 | 0,00 |
| Transport of contaminated soil (boat+truck) | MSEK | 0,85 | 0,85 | 0,85 |
| Transport of contaminated soil (truck) | MSEK | 1,09 | 1,09 | 1,09 |
| Landfilling of non-hazardous soil | MSEK | 1,69 | 0,93 | 2,45 |
| Landfilling of hazardous soil | MSEK | 1,71 | 1,03 | 2,39 |
| Landfilling of hazardous soil (including tar in free PAHe) | MSEK | 2,22 | 1,13 | 3,31 |
| Pristine soil (including transport and refill) | MSEK | 0,98 | 0,78 | 1,18 |
| ISCO (persulfate) (same price for soil and GW) | MSEK | 35,18 | 35,18 | 35,18 |
| S/S (total) | MSEK | 59,42 | 55,38 | 63,46 |

| | | | | |
|---|---|---|---|---|
| ISTD | MSEK | 0,00 | 0,00 | 0,00 |
| Bioremediation | MSEK | 0,00 | 0,00 | 0,00 |
| Other costs (design, builder etc.) | MSEK | 12,78 | 11,75 | 13,81 |
| Unforeseen | MSEK | 19,17 | 17,62 | 20,72 |
| **Total Scenario 1a** | **MSEK** | **158,66** | **145,75** | **171,58** |
| **Total Scenario 1b** | **MSEK** | **158,90** | **145,99** | **171,82** |

- *Alternative 3*

| **Action** | **Unit** | **Alt. 3** | | |
|---|---|---|---|---|
| | | Mean | Min | Max |
| Excavation and sorting | MSEK | 3,61 | 2,88 | 4,33 |
| Environmental inspection (sampling, 2 persons) | MSEK | 7,50 | 6,00 | 9,00 |
| Environmental control (chemical analysis) | MSEK | 0,83 | 0,66 | 0,99 |
| Sheet piling | MSEK | 20,19 | 17,31 | 23,08 |
| Setting of storage areas and water treatment area | MSEK | 0,30 | 0,30 | 0,30 |
| Water purification including pumping and 'lowering' of GW | MSEK | 0,23 | 0,08 | 0,39 |
| Transport of contaminated soil (boat+truck) | MSEK | 4,25 | 4,25 | 4,25 |
| Transport of contaminated soil (truck) | MSEK | 5,44 | 5,44 | 5,44 |
| Landfilling of non-hazardous soil | MSEK | 0,23 | 0,08 | 0,39 |
| Landfilling of hazardous soil | MSEK | 8,46 | 4,66 | 12,26 |
| Landfilling of hazardous soil (including tar in free PAHe) | MSEK | 8,54 | 5,15 | 11,93 |
| Pristine soil (including transport and refill) | MSEK | 11,11 | 5,66 | 16,55 |
| ISCO (persulfate) (same price for soil and GW) | MSEK | 0,00 | 0,00 | 0,00 |
| S/S (total) | MSEK | 0,00 | 0,00 | 0,00 |
| ISTD | MSEK | 0,00 | 0,00 | 0,00 |
| Bioremediation | MSEK | 44,44 | 44,44 | 44,44 |
| Other costs (design, builder etc.) | MSEK | 11,33 | 9,62 | 13,03 |
| Unforeseen | MSEK | 16,99 | 14,42 | 19,55 |
| **Total Scenario 1a** | **MSEK** | **138,46** | **115,69** | **161,20** |
| **Total Scenario 1b** | **MSEK** | **139,66** | **116,89** | **162,40** |

- *Alternative 4*

| **Action** | **Unit** | **Alt. 4** | | |
|---|---|---|---|---|
| | | Mean | Min | Max |
| Excavation and sorting | MSEK | 0,72 | 0,58 | 0,87 |
| Environmental inspection (sampling, 2 persons) | MSEK | 6,00 | 9,00 | 7,50 |
| Environmental control (chemical analysis) | MSEK | 0,83 | 0,66 | 0,99 |
| Sheet piling | MSEK | 20,19 | 17,31 | 23,08 |
| Setting of storage areas and water treatment area | MSEK | 0,30 | 0,30 | 0,30 |
| Water purification including pumping and 'lowering' of GW | MSEK | 0,00 | 0,00 | 0,00 |
| Transport of contaminated soil (boat+truck) | MSEK | 0,85 | 0,85 | 0,85 |
| Transport of contaminated soil (truck) | MSEK | 1,09 | 1,09 | 1,09 |
| Landfilling of non-hazarodus soil | MSEK | 1,69 | 0,93 | 2,45 |
| Landfilling of hazardous soil | MSEK | 1,71 | 1,03 | 2,39 |
| Landfilling of hazardous soil (including tar in free PAHe) | MSEK | 2,22 | 1,13 | 3,31 |

| | | | | |
|---|---|---|---|---|
| Pristine soil (including transport and refill) | MSEK | 0,98 | 0,78 | 1,18 |
| ISCO (persulfate) (same price for soil and GW) | MSEK | 0,00 | 0,00 | 0,00 |
| S/S (total) | MSEK | 59,42 | 55,38 | 63,46 |
| ISTD | MSEK | 0,00 | 0,00 | 0,00 |
| Bioremediation | MSEK | 44,44 | 44,44 | 44,44 |
| Other costs (design, builder etc.) | MSEK | 14,01 | 12,97 | 15,04 |
| Unforeseen | MSEK | 21,01 | 19,46 | 22,56 |
| **Total Scenario 1a** | **MSEK** | **176,33** | **162,01** | **190,65** |
| **Total Scenario 1b** | **MSEK** | **176,57** | **162,25** | **190,89** |

- *Alternative 5*

| **Action** | **Unit** | **Alt. 5** | | |
|---|---|---|---|---|
| | | Mean | Min | Max |
| Excavation and sorting | MSEK | 3,61 | 2,88 | 4,33 |
| Environmental inspection (sampling, 2 persons) | MSEK | 2,63 | 2,25 | 3,00 |
| Environmental control (chemical analysis) | MSEK | 0,83 | 0,66 | 0,99 |
| Sheet piling | MSEK | 20,19 | 17,31 | 23,08 |
| Setting of storage areas and water treatment area | MSEK | 0,30 | 0,30 | 0,30 |
| Water purification including pumping and 'lowering' of GW | MSEK | 0,23 | 0,08 | 0,39 |
| Transport of contaminated soil (boat+truck) | MSEK | 4,25 | 4,25 | 4,25 |
| Transport of contaminated soil (truck) | MSEK | 5,44 | 5,44 | 5,44 |
| Landfilling of non-hazarodus soil | MSEK | 8,46 | 4,66 | 12,26 |
| Landfilling of hazardous soil | MSEK | 8,54 | 5,15 | 11,93 |
| Landfilling of hazardous soil (including tar in free PAHe) | MSEK | 11,11 | 5,66 | 16,55 |
| Pristine soil (including transport and refill) | MSEK | 4,90 | 3,92 | 5,88 |
| ISCO (persulfate) (same price for soil and GW) | MSEK | 0,00 | 0,00 | 0,00 |
| S/S (total) | MSEK | 0,00 | 0,00 | 0,00 |
| ISTD | MSEK | 92,31 | 92,31 | 92,31 |
| Bioremediation | MSEK | 0,00 | 0,00 | 0,00 |
| Other costs (design, builder etc.) | MSEK | 16,28 | 14,49 | 18,07 |
| Unforeseen | MSEK | 24,42 | 21,73 | 27,11 |
| **Total Scenario 1a** | **MSEK** | **198,05** | **175,65** | **220,44** |
| **Total Scenario 1b** | **MSEK** | **199,24** | **176,84** | **221,63** |

**Costs of Impaired Health due to Remedial Actions**

| | $CO_2$ | | | $SO_2$ | | | $NO_x$ | | |
|---|---|---|---|---|---|---|---|---|---|
| | Mean | Min | Max | Mean | Min | Max | Mean | Min | Max |
| Price (eur/ton) | 23.8 | 9.5 | 38.1 | 19184 | 9792 | 28576 | 8192.5 | 4419 | 11966 |
| Price (SEK/ton) | 253.2 | 101 | 405.3 | 204085 | 104170 | 304000 | 87154 | 47011 | 127298 |

- *Alternative 1*

| | $CO_2$ (kg eq) | $SO_2$ (kg eq) | $NO_x$ (kg eq) |
|---|---|---|---|
| Scenario 1a | 1303950 | 4611 | 8615 |

| | | | |
|---|---|---|---|
| Scenario 1b | 1335623 | 3663 | 4729 |

| | Scenario 1a | Scenario 1b |
|---|---|---|
| Price (MSEK) | 0.018 | 0.013 |

- *Alternative 2*

| | $CO_2$ (kg eq) | $SO_2$ (kg eq) | $NO_x$ (kg eq) |
|---|---|---|---|
| Scenario 1a | 1413902 | 2772 | 3658 |
| Scenario 1b | 1420237 | 2583 | 2881 |

| | Scenario 1a | Scenario 1b |
|---|---|---|
| Price (MSEK) | 0.011 | 0.010 |

- *Alternative 3*

| | $CO_2$ (kg eq) | $SO_2$ (kg eq) | $NO_x$ (kg eq) |
|---|---|---|---|
| Scenario 1a | 1304632 | 4565 | 8547 |
| Scenario 1b | 1336305 | 3617 | 4660 |

| | Scenario 1a | Scenario 1b |
|---|---|---|
| Price (MSEK) | 0.018 | 0.013 |

- *Alternative 4*

| | $CO_2$ (kg eq) | $SO_2$ (kg eq) | $NO_x$ (kg eq) |
|---|---|---|---|
| Scenario 1a | 1433298 | 2850 | 3697 |
| Scenario 1b | 1439632 | 2661 | 2920 |

| | Scenario 1a | Scenario 1b |
|---|---|---|
| Price (MSEK) | 0.011 | 0.010 |

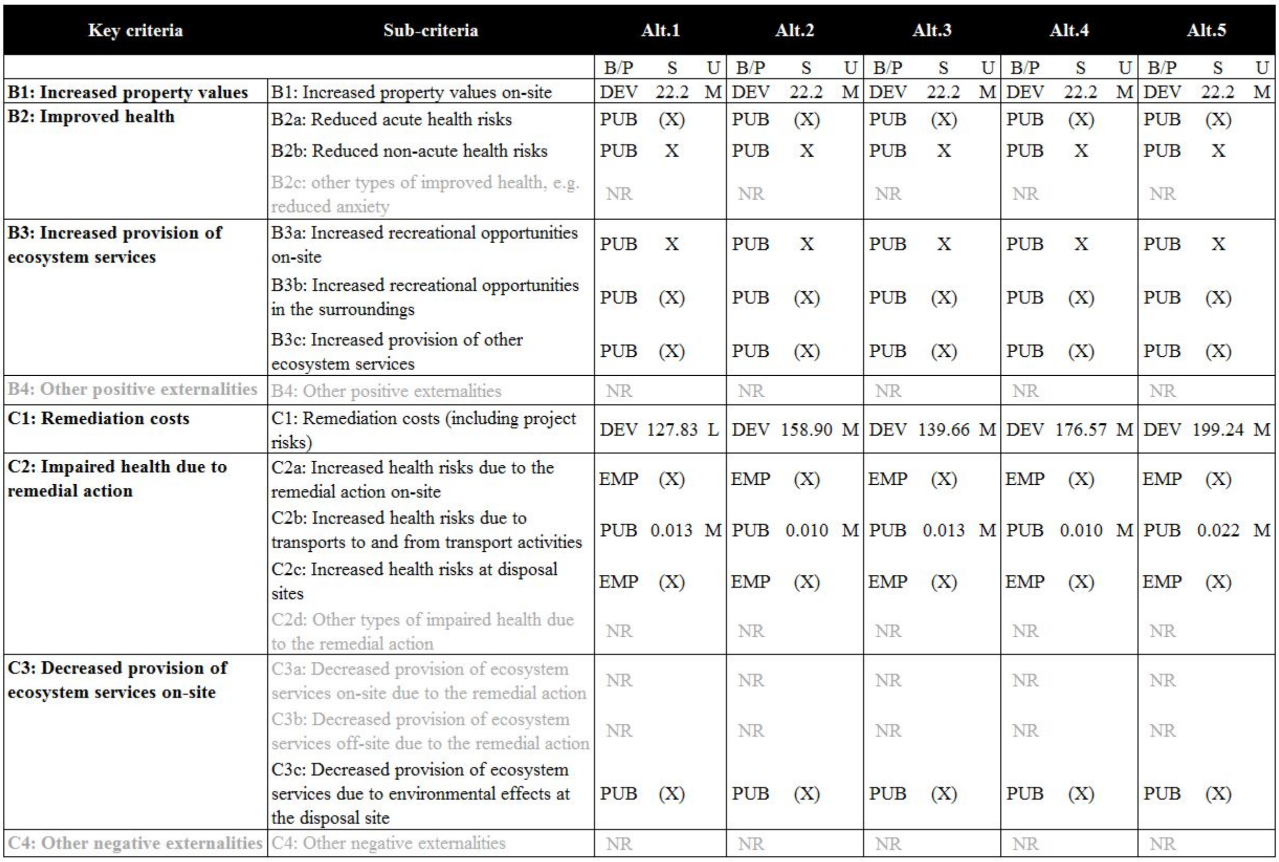
- *Alternative 5*

| | $CO_2$ (kg eq) | $SO_2$ (kg eq) | $NO_x$ (kg eq) |
|---|---|---|---|
| Scenario 1a | 3084770 | 7031 | 8532 |
| Scenario 1b | 3116444 | 6083 | 4645 |

| | Scenario 1a | Scenario 1b |
|---|---|---|
| Price (MSEK) | 0.026 | 0.022 |

- **SCORE Inputs of Scenario I, II and III b**

*Table A 9. SCORE inputs for the economic domain.*

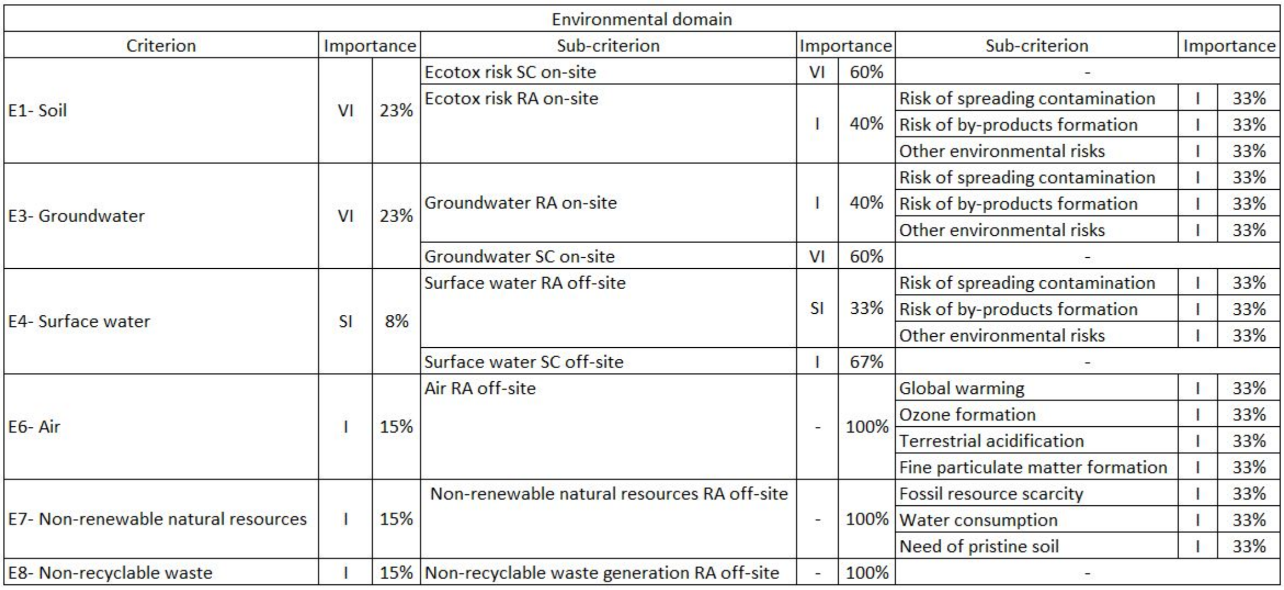


| Key criteria | Sub-criteria | Alt.1 | | | Alt.2 | | | Alt.3 | | | Alt.4 | | | Alt.5 | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | B/P | S | U | B/P | S | U | B/P | S | U | B/P | S | U | B/P | S | U |
| **B1: Increased property values** | B1: Increased property values on-site | DEV | 22.2 | M | DEV | 22.2 | M | DEV | 22.2 | M | DEV | 22.2 | M | DEV | 22.2 | M |
| **B2: Improved health** | B2a: Reduced acute health risks | PUB | (X) | | PUB | (X) | | PUB | (X) | | PUB | (X) | | PUB | (X) | |
| | B2b: Reduced non-acute health risks | PUB | X | | PUB | X | | PUB | X | | PUB | X | | PUB | X | |
| | B2c: other types of improved health, e.g. reduced anxiety | NR | | | NR | | | NR | | | NR | | | NR | | |
| **B3: Increased provision of ecosystem services** | B3a: Increased recreational opportunities on-site | PUB | X | | PUB | X | | PUB | X | | PUB | X | | PUB | X | |
| | B3b: Increased recreational opportunities in the surroundings | PUB | (X) | | PUB | (X) | | PUB | (X) | | PUB | (X) | | PUB | (X) | |
| | B3c: Increased provision of other ecosystem services | PUB | (X) | | PUB | (X) | | PUB | (X) | | PUB | (X) | | PUB | (X) | |
| **B4: Other positive externalities** | B4: Other positive externalities | NR | | | NR | | | NR | | | NR | | | NR | | |
| **C1: Remediation costs** | C1: Remediation costs (including project risks) | DEV | 127.83 | L | DEV | 158.90 | M | DEV | 139.66 | M | DEV | 176.57 | M | DEV | 199.24 | M |
| **C2: Impaired health due to remedial action** | C2a: Increased health risks due to the remedial action on-site | EMP | (X) | | EMP | (X) | | EMP | (X) | | EMP | (X) | | EMP | (X) | |
| | C2b: Increased health risks due to transports to and from transport activities | PUB | 0.013 | M | PUB | 0.010 | M | PUB | 0.013 | M | PUB | 0.010 | M | PUB | 0.022 | M |
| | C2c: Increased health risks at disposal sites | EMP | (X) | | EMP | (X) | | EMP | (X) | | EMP | (X) | | EMP | (X) | |
| | C2d: Other types of impaired health due to the remedial action | NR | | | NR | | | NR | | | NR | | | NR | | |
| **C3: Decreased provision of ecosystem services on-site** | C3a: Decreased provision of ecosystem services on-site due to the remedial action | NR | | | NR | | | NR | | | NR | | | NR | | |
| | C3b: Decreased provision of ecosystem services off-site due to the remedial action | NR | | | NR | | | NR | | | NR | | | NR | | |
| | C3c: Decreased provision of ecosystem services due to environmental effects at the disposal site | PUB | (X) | | PUB | (X) | | PUB | (X) | | PUB | (X) | | PUB | (X) | |
| **C4: Other negative externalities** | C4: Other negative externalities | NR | | | NR | | | NR | | | NR | | | NR | | |

# Appendix VIII – Weighting of the Criteria and Subcriteria

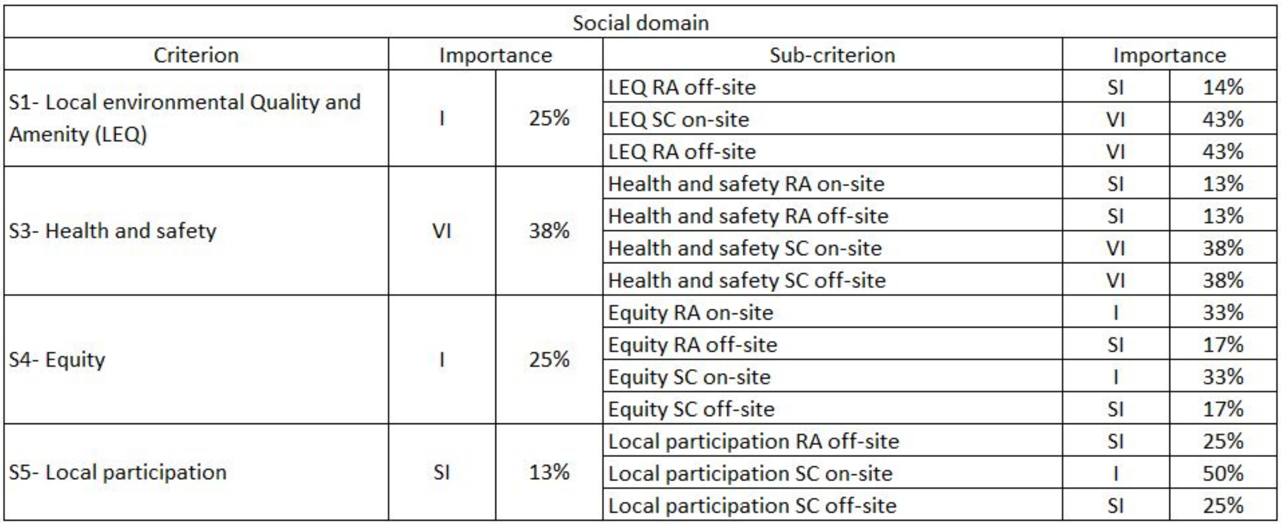
Tables A10 and A11 show the weighting of the environmental and social criteria and subcriteria for the main scenarios (I, II and III a and b). Relatively to the importance, SI=somewhat important, I=important and VI=very important. The percentage of the importance was calculated by SCORE.

*Table A 10. Weighting of the environmental criteria.*



| Environmental domain | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| Criterion | Importance | | Sub-criterion | Importance | | Sub-criterion | Importance | |
| E1- Soil | VI | 23% | Ecotox risk SC on-site | VI | 60% | - | | |
| | | | Ecotox risk RA on-site | I | 40% | Risk of spreading contamination | I | 33% |
| | | | | | | Risk of by-products formation | I | 33% |
| | | | | | | Other environmental risks | I | 33% |
| E3- Groundwater | VI | 23% | Groundwater RA on-site | I | 40% | Risk of spreading contamination | I | 33% |
| | | | | | | Risk of by-products formation | I | 33% |
| | | | | | | Other environmental risks | I | 33% |
| | | | Groundwater SC on-site | VI | 60% | - | | |
| E4- Surface water | SI | 8% | Surface water RA off-site | SI | 33% | Risk of spreading contamination | I | 33% |
| | | | | | | Risk of by-products formation | I | 33% |
| | | | | | | Other environmental risks | I | 33% |
| | | | Surface water SC off-site | I | 67% | - | | |
| E6- Air | I | 15% | Air RA off-site | - | 100% | Global warming | I | 33% |
| | | | | | | Ozone formation | I | 33% |
| | | | | | | Terrestrial acidification | I | 33% |
| | | | | | | Fine particulate matter formation | I | 33% |
| E7- Non-renewable natural resources | I | 15% | Non-renewable natural resources RA off-site | - | 100% | Fossil resource scarcity | I | 33% |
| | | | | | | Water consumption | I | 33% |
| | | | | | | Need of pristine soil | I | 33% |
| E8- Non-recyclable waste | I | 15% | Non-recyclable waste generation RA off-site | - | 100% | - | | |

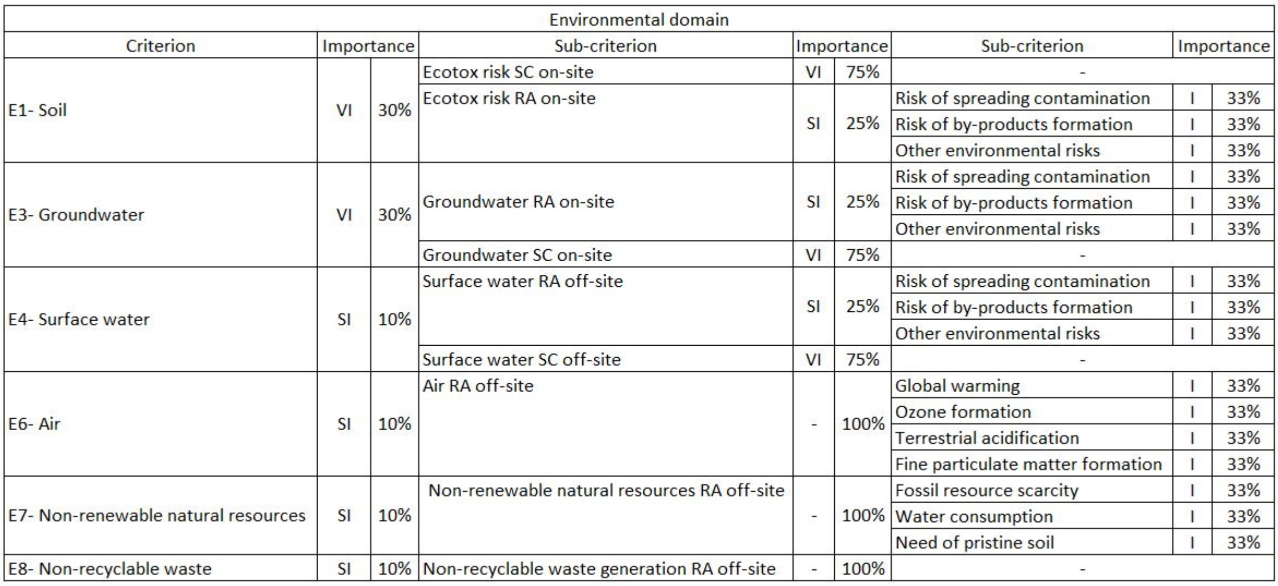
*Table A 11. Weighting of the social criteria.*



| Social domain | | | | | |
|---|---|---|---|---|---|
| Criterion | Importance | | Sub-criterion | Importance | |
| S1- Local environmental Quality and Amenity (LEQ) | I | 25% | LEQ RA off-site | SI | 14% |
| | | | LEQ SC on-site | VI | 43% |
| | | | LEQ RA off-site | VI | 43% |
| S3- Health and safety | VI | 38% | Health and safety RA on-site | SI | 13% |
| | | | Health and safety RA off-site | SI | 13% |
| | | | Health and safety SC on-site | VI | 38% |
| | | | Health and safety SC off-site | VI | 38% |
| S4- Equity | I | 25% | Equity RA on-site | I | 33% |
| | | | Equity RA off-site | SI | 17% |
| | | | Equity SC on-site | I | 33% |
| | | | Equity SC off-site | SI | 17% |
| S5- Local participation | SI | 13% | Local participation RA off-site | SI | 25% |
| | | | Local participation SC on-site | I | 50% |
| | | | Local participation SC off-site | SI | 25% |

Table A12 shows the weighting of the environmental criteria and subcriteria for Scenario x.

*Table A 12. Weighting of the environmental criteria and subcriteria for scenario x.*



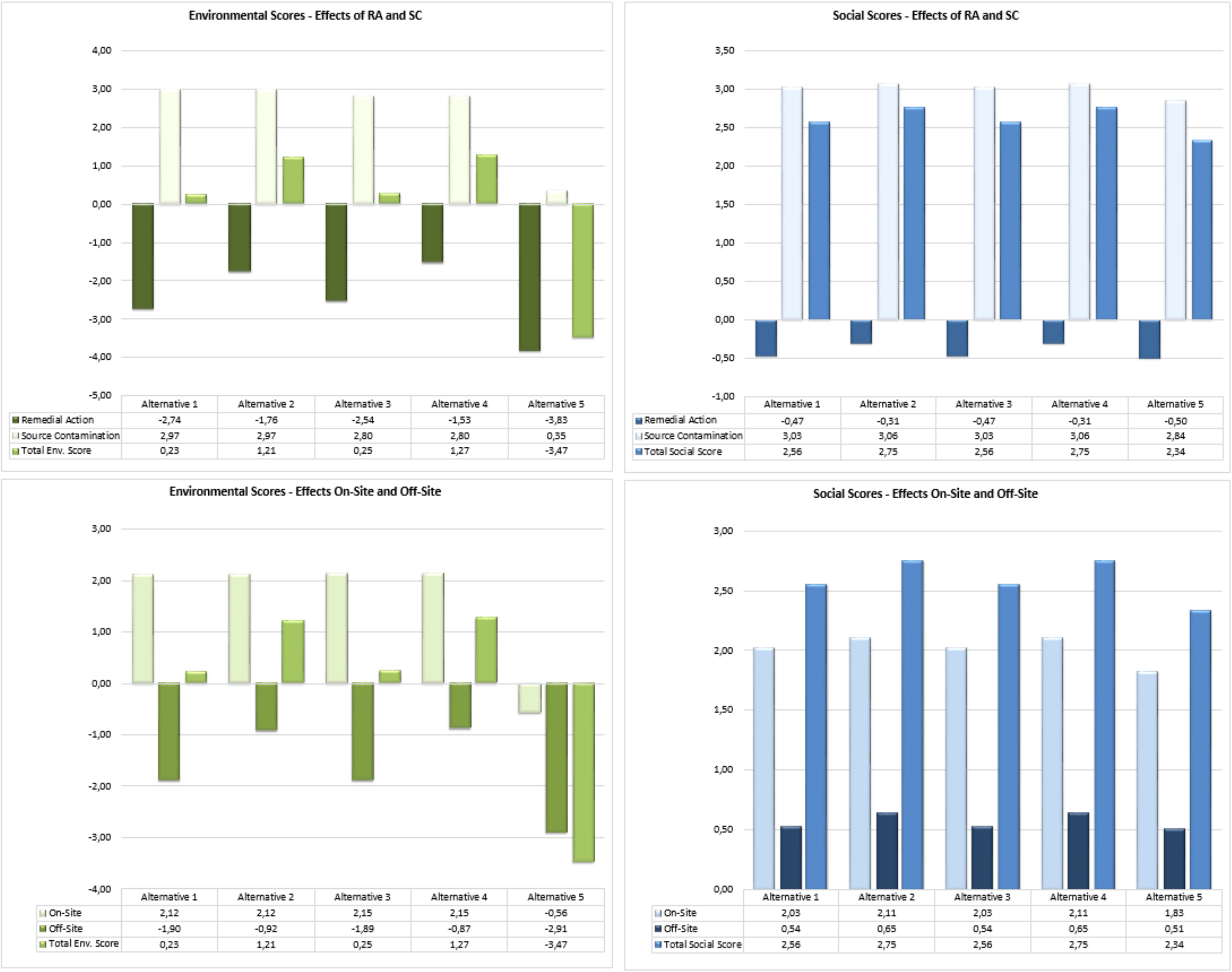
| Environmental domain | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| Criterion | Importance | | Sub-criterion | Importance | | Sub-criterion | Importance | |
| E1- Soil | VI | 30% | Ecotox risk SC on-site | VI | 75% | - | | |
| | | | Ecotox risk RA on-site | SI | 25% | Risk of spreading contamination | I | 33% |
| | | | | | | Risk of by-products formation | I | 33% |
| | | | | | | Other environmental risks | I | 33% |
| E3- Groundwater | VI | 30% | Groundwater RA on-site | SI | 25% | Risk of spreading contamination | I | 33% |
| | | | | | | Risk of by-products formation | I | 33% |
| | | | | | | Other environmental risks | I | 33% |
| | | | Groundwater SC on-site | VI | 75% | - | | |
| E4- Surface water | SI | 10% | Surface water RA off-site | SI | 25% | Risk of spreading contamination | I | 33% |
| | | | | | | Risk of by-products formation | I | 33% |
| | | | | | | Other environmental risks | I | 33% |
| | | | Surface water SC off-site | VI | 75% | - | | |
| E6- Air | SI | 10% | Air RA off-site | - | 100% | Global warming | I | 33% |
| | | | | | | Ozone formation | I | 33% |
| | | | | | | Terrestrial acidification | I | 33% |
| | | | | | | Fine particulate matter formation | I | 33% |
| E7- Non-renewable natural resources | SI | 10% | Non-renewable natural resources RA off-site | - | 100% | Fossil resource scarcity | I | 33% |
| | | | | | | Water consumption | I | 33% |
| | | | | | | Need of pristine soil | I | 33% |
| E8- Non-recyclable waste | SI | 10% | Non-recyclable waste generation RA off-site | - | 100% | - | | |

# Appendix IX – Results of the main scenarios

The results mentioned in Section 6 that were not shown in the text are instead shown here.

## Scenario I

*Figure A 19. Sensitivity analysis of the results of scenario Ib.*



Environmental Scores - Effects of RA and SC

| | Alternative 1 | Alternative 2 | Alternative 3 | Alternative 4 | Alternative 5 |
|---|---|---|---|---|---|
| Remedial Action | -2,74 | -1,76 | -2,54 | -1,53 | -3,83 |
| Source Contamination | 2,97 | 2,97 | 2,80 | 2,80 | 0,35 |
| Total Env. Score | 0,23 | 1,21 | 0,25 | 1,27 | -3,47 |

Social Scores - Effects of RA and SC

| | Alternative 1 | Alternative 2 | Alternative 3 | Alternative 4 | Alternative 5 |
|---|---|---|---|---|---|
| Remedial Action | -0,47 | -0,31 | -0,47 | -0,31 | -0,50 |
| Source Contamination | 3,03 | 3,06 | 3,03 | 3,06 | 2,84 |
| Total Social Score | 2,56 | 2,75 | 2,56 | 2,75 | 2,34 |

Environmental Scores - Effects On-Site and Off-Site

| | Alternative 1 | Alternative 2 | Alternative 3 | Alternative 4 | Alternative 5 |
|---|---|---|---|---|---|
| On-Site | 2,12 | 2,12 | 2,15 | 2,15 | -0,56 |
| Off-Site | -1,90 | -0,92 | -1,89 | -0,87 | -2,91 |
| Total Env. Score | 0,23 | 1,21 | 0,25 | 1,27 | -3,47 |

Social Scores - Effects On-Site and Off-Site

| | Alternative 1 | Alternative 2 | Alternative 3 | Alternative 4 | Alternative 5 |
|---|---|---|---|---|---|
| On-Site | 2,03 | 2,11 | 2,03 | 2,11 | 1,83 |
| Off-Site | 0,54 | 0,65 | 0,54 | 0,65 | 0,51 |
| Total Social Score | 2,56 | 2,75 | 2,56 | 2,75 | 2,34 |

*Figure A 20. Ecological and social effects of the remediation alternatives (scenario Ib).*

## Scenario II

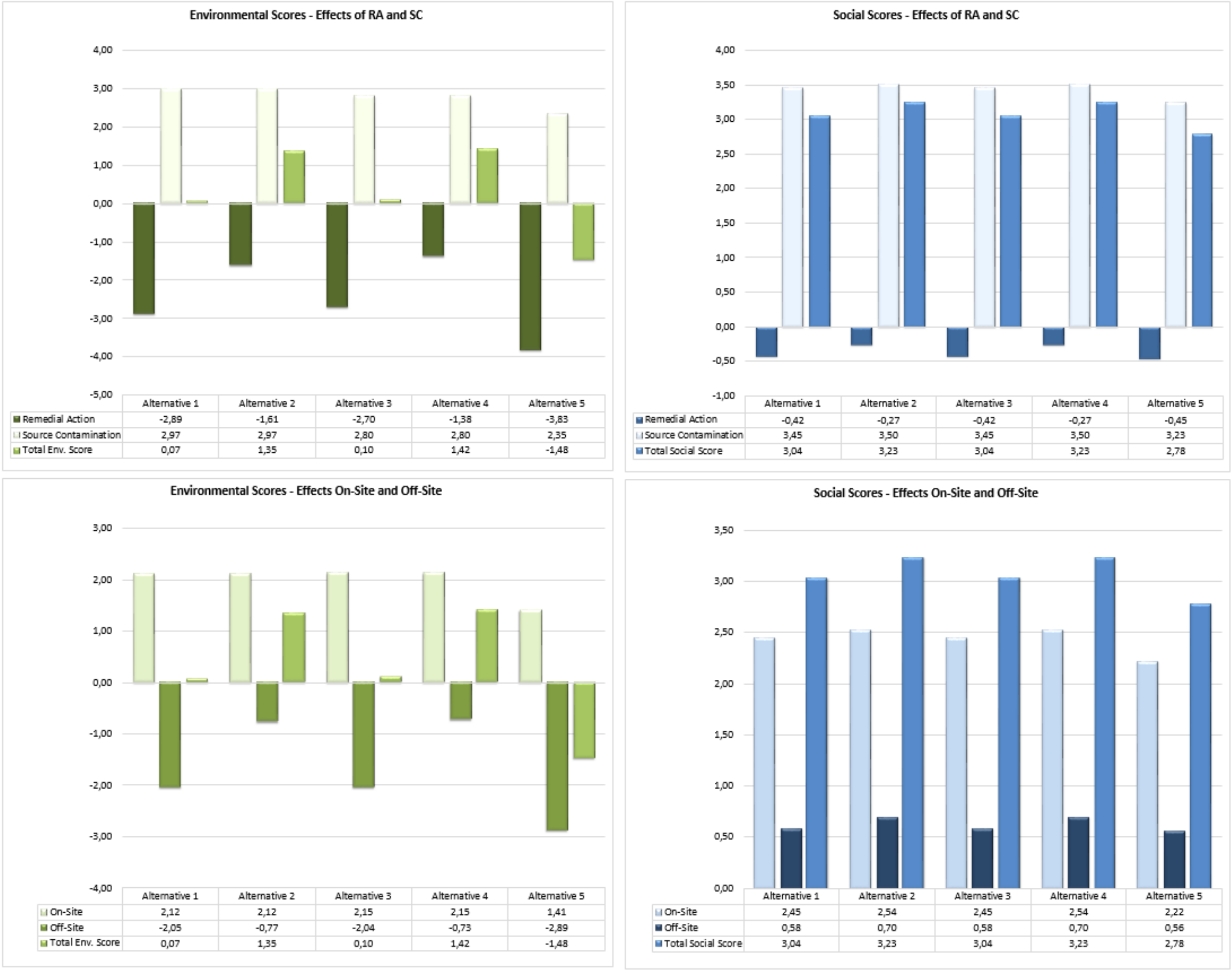


*Figure A 21. Ecological and social effects of the remediation alternatives (scenario IIa).*

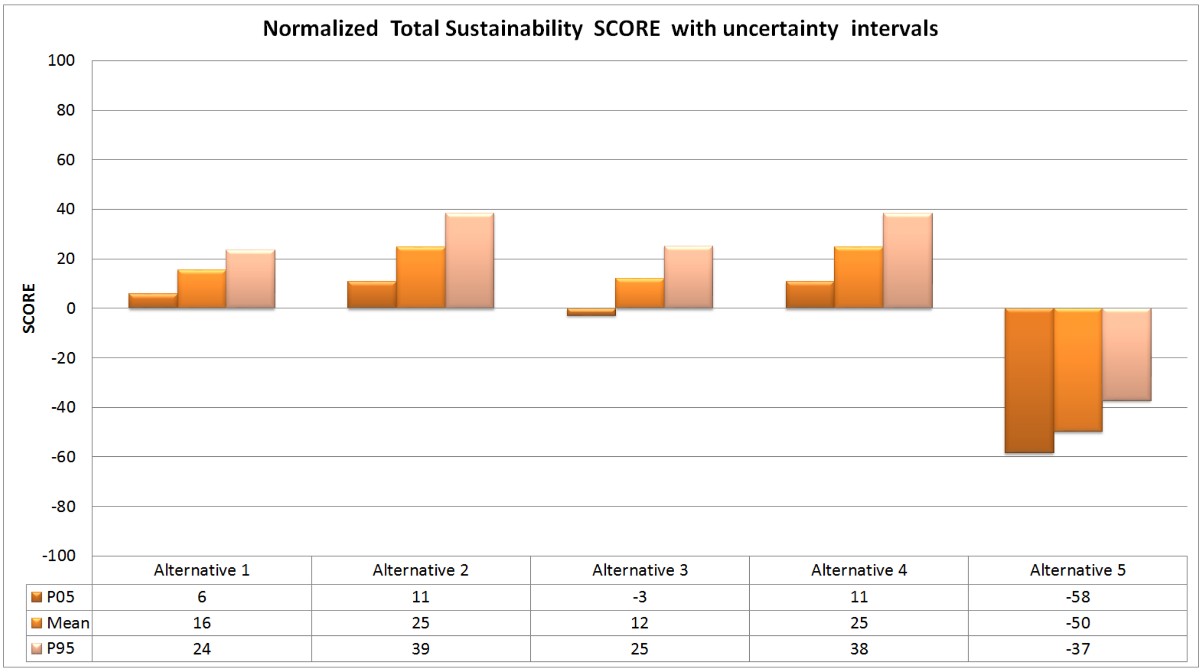


*Figure A 22. Normalized total sustainability scores with uncertainty intervals for scenario IIb.*

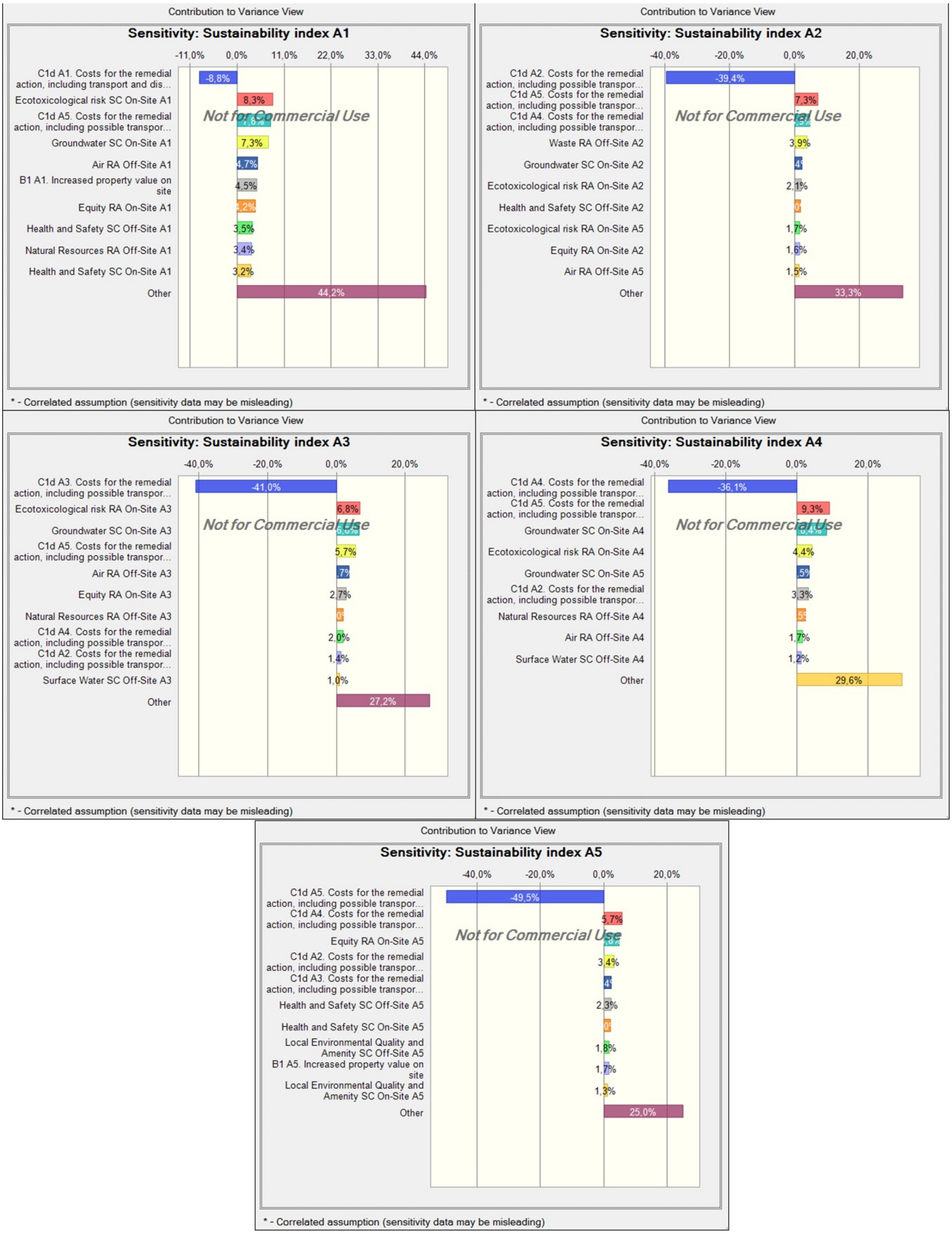


*Figure A 23. Sensitivity analysis for scenario IIb.*

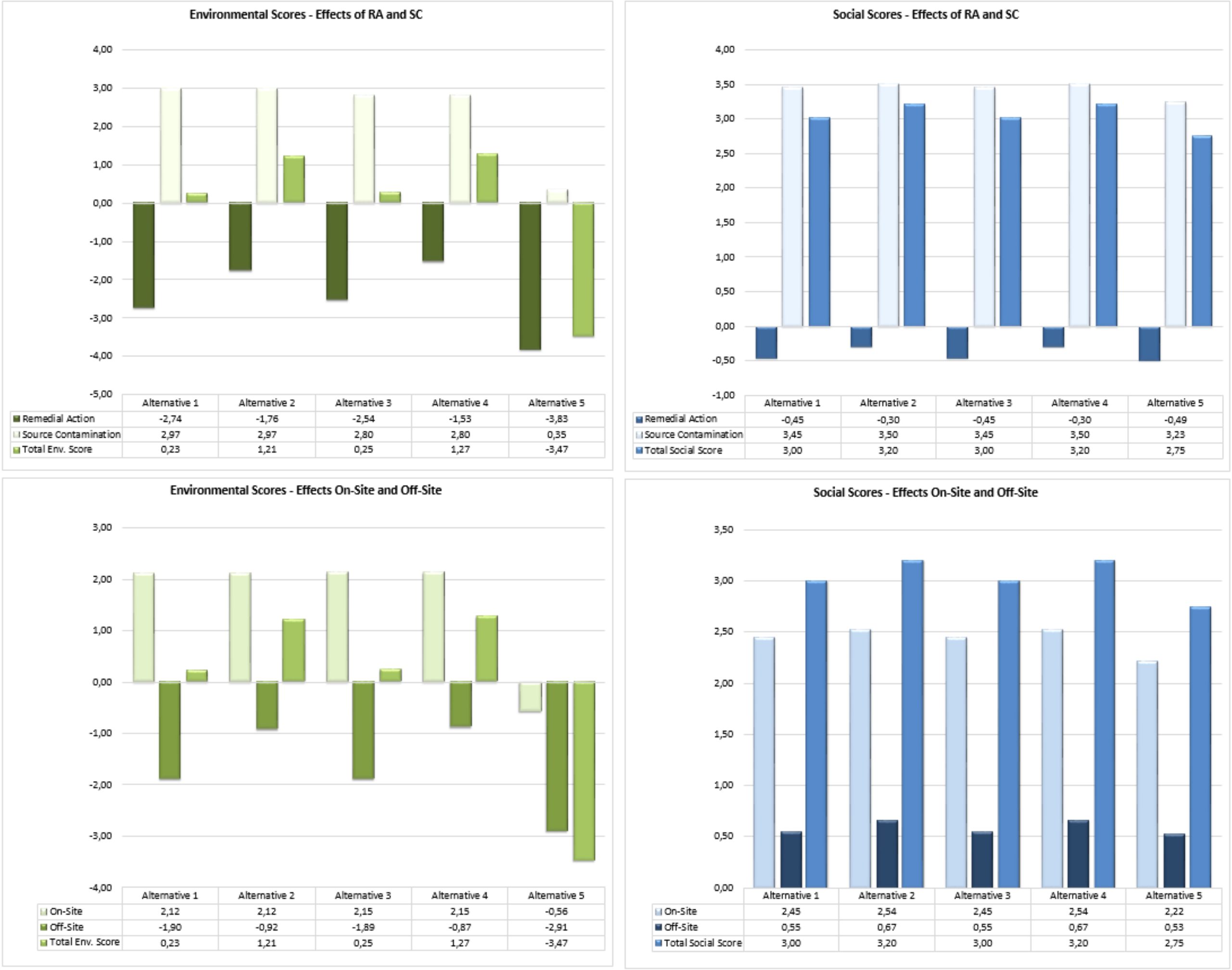


*Figure A 24. Ecological and social effects of the remediation alternatives (scenario IIb)*

## Scenario III

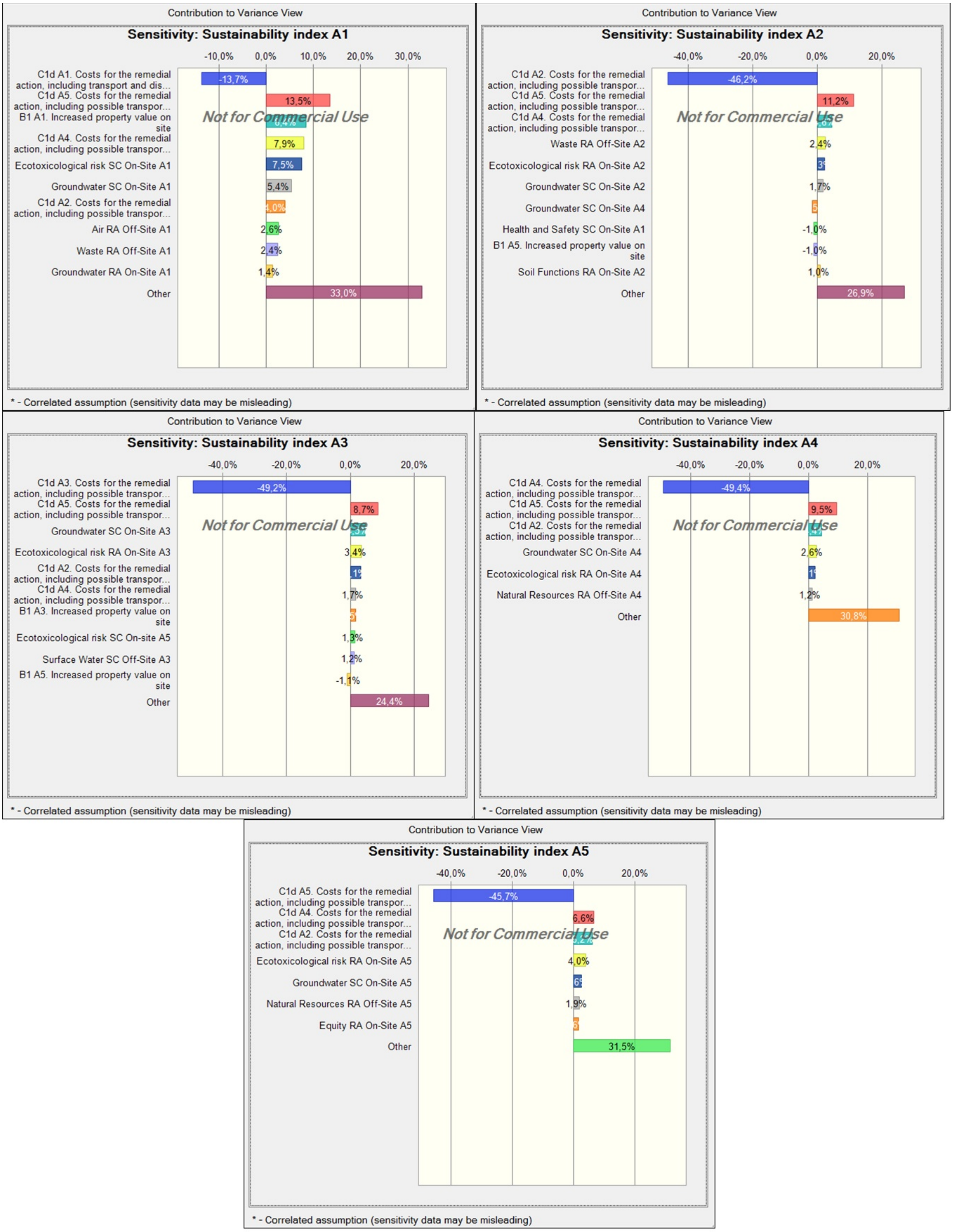
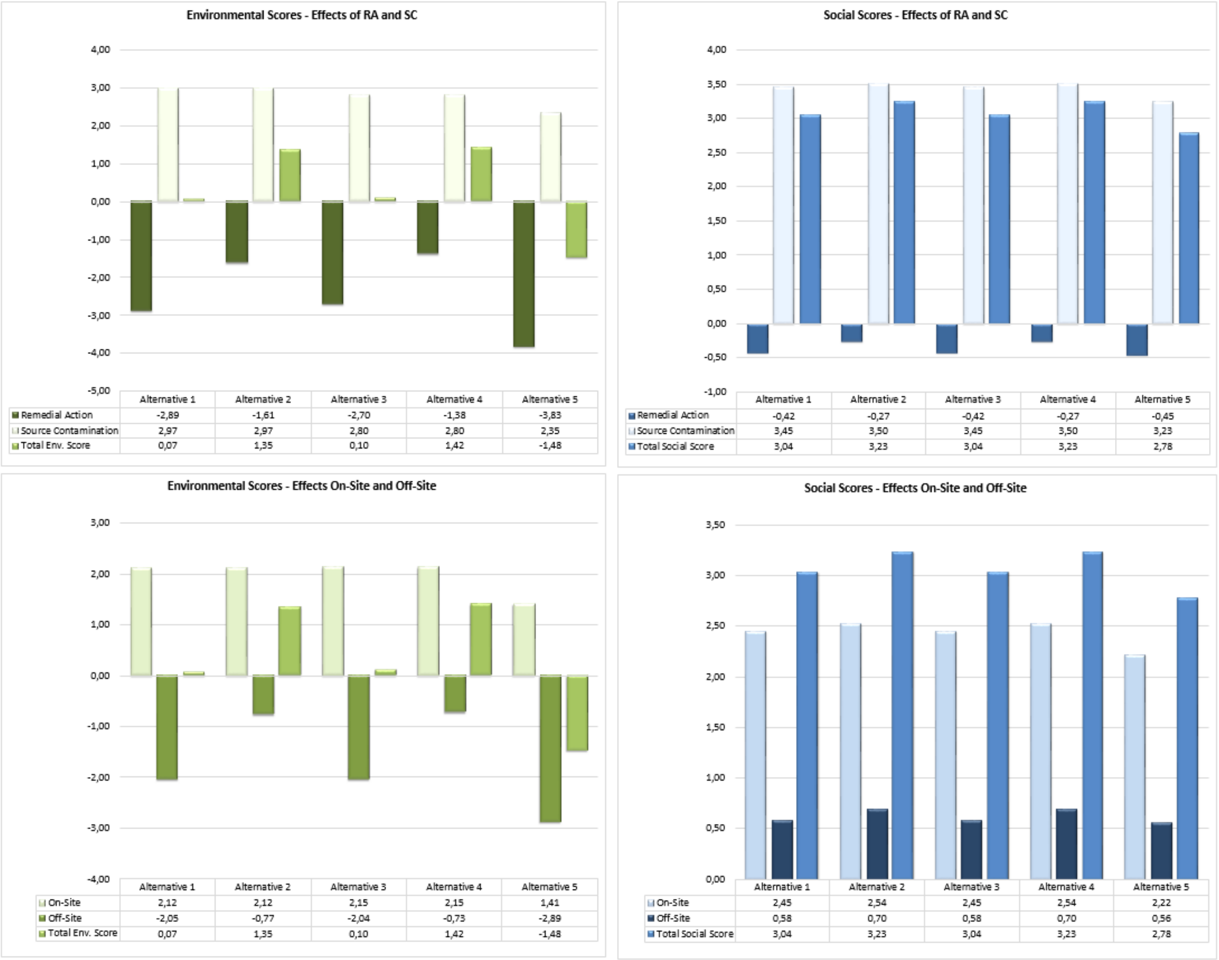


*Figure A 25. Sensitivity analysis for scenario IIIa.*



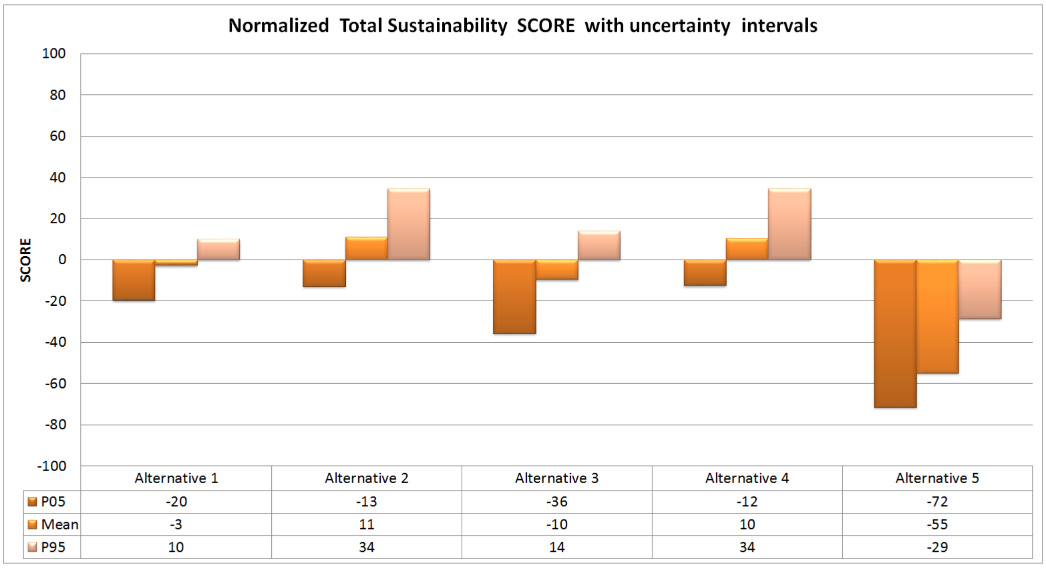
| | Alternative 1 | Alternative 2 | Alternative 3 | Alternative 4 | Alternative 5 |
|---|---|---|---|---|---|
| Remedial Action | -2,89 | -1,61 | -2,70 | -1,38 | -3,83 |
| Source Contamination | 2,97 | 2,97 | 2,80 | 2,80 | 2,35 |
| Total Env. Score | 0,07 | 1,35 | 0,10 | 1,42 | -1,48 |

| | Alternative 1 | Alternative 2 | Alternative 3 | Alternative 4 | Alternative 5 |
|---|---|---|---|---|---|
| Remedial Action | -0,42 | -0,27 | -0,42 | -0,27 | -0,45 |
| Source Contamination | 3,45 | 3,50 | 3,45 | 3,50 | 3,23 |
| Total Social Score | 3,04 | 3,23 | 3,04 | 3,23 | 2,78 |

| | Alternative 1 | Alternative 2 | Alternative 3 | Alternative 4 | Alternative 5 |
|---|---|---|---|---|---|
| On-Site | 2,12 | 2,12 | 2,15 | 2,15 | 1,41 |
| Off-Site | -2,05 | -0,77 | -2,04 | -0,73 | -2,89 |
| Total Env. Score | 0,07 | 1,35 | 0,10 | 1,42 | -1,48 |

| | Alternative 1 | Alternative 2 | Alternative 3 | Alternative 4 | Alternative 5 |
|---|---|---|---|---|---|
| On-Site | 2,45 | 2,54 | 2,45 | 2,54 | 2,22 |
| Off-Site | 0,58 | 0,70 | 0,58 | 0,70 | 0,56 |
| Total Social Score | 3,04 | 3,23 | 3,04 | 3,23 | 2,78 |

*Figure A 26. Ecological and social effects of the remediation alternatives (scenario IIIa).*



| | Alternative 1 | Alternative 2 | Alternative 3 | Alternative 4 | Alternative 5 |
|---|---|---|---|---|---|
| P05 | -20 | -13 | -36 | -12 | -72 |
| Mean | -3 | 11 | -10 | 10 | -55 |
| P95 | 10 | 34 | 14 | 34 | -29 |

*Figure A 27. Normalized sustainability scores with uncertainty intervals for scenario IIIb.*

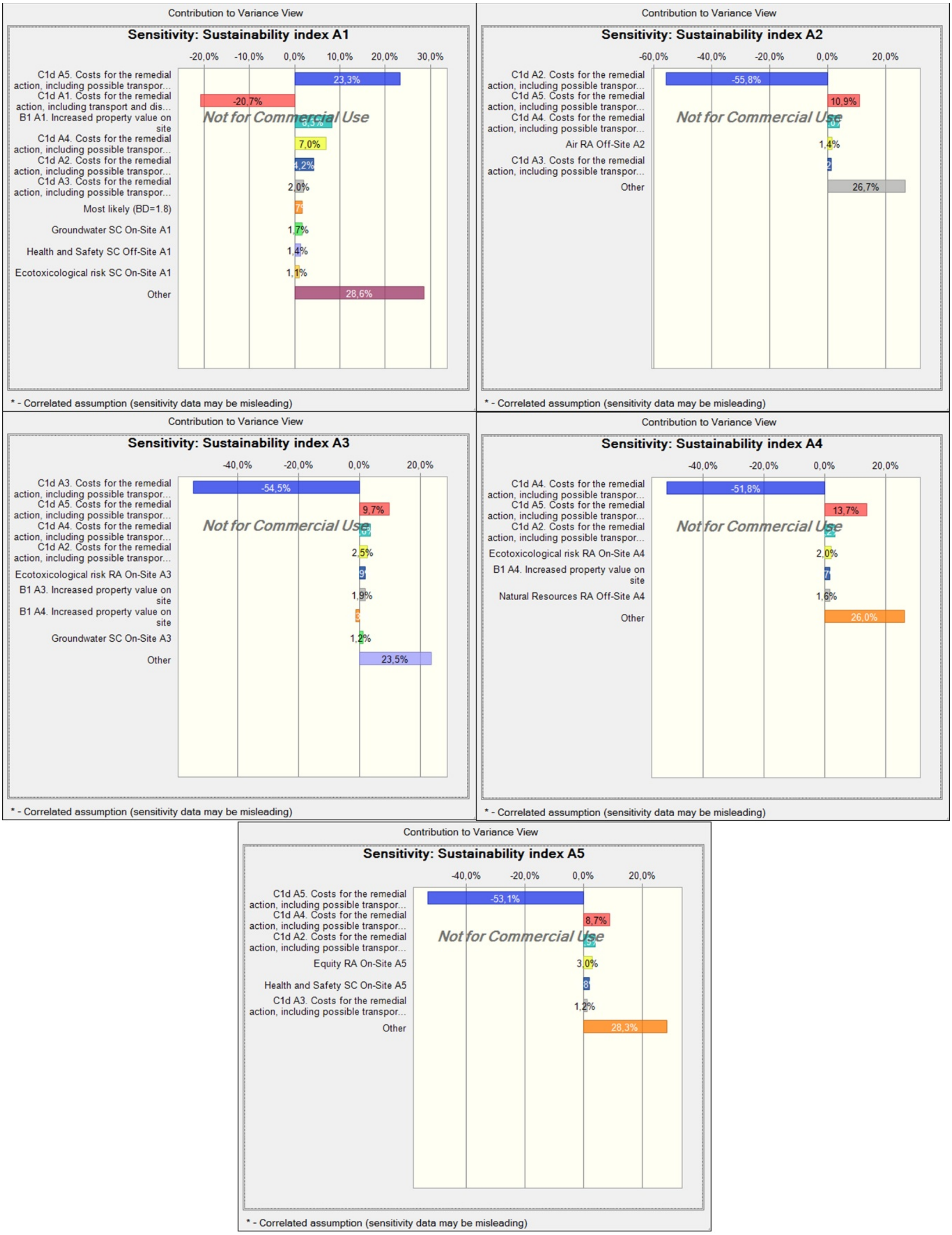
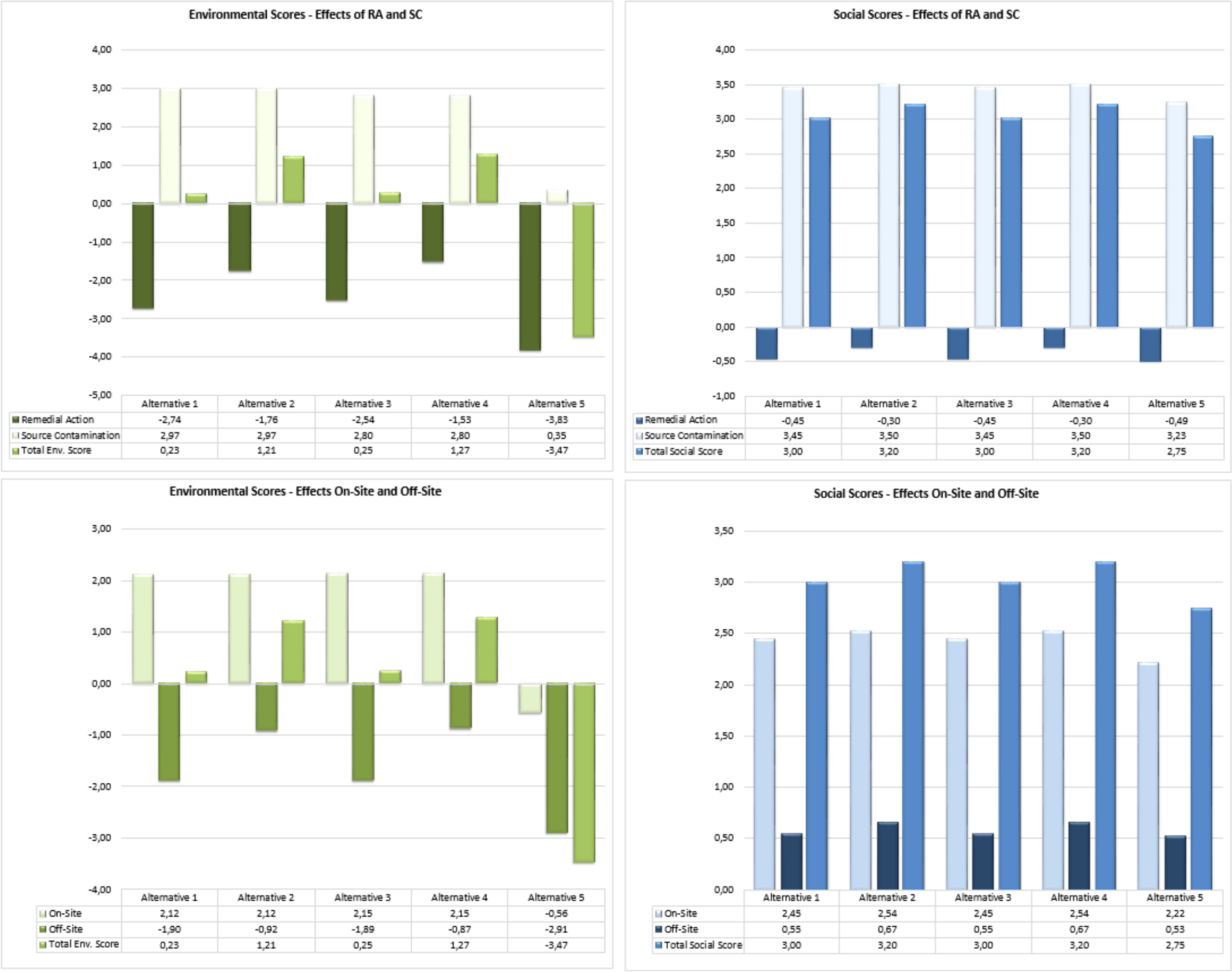


*Figure A 28. Sensitivity analysis for scenario IIIb.*



| | Alternative 1 | Alternative 2 | Alternative 3 | Alternative 4 | Alternative 5 |
|---|---|---|---|---|---|
| Remedial Action | -2,74 | -1,76 | -2,54 | -1,53 | -3,83 |
| Source Contamination | 2,97 | 2,97 | 2,80 | 2,80 | 0,35 |
| Total Env. Score | 0,23 | 1,21 | 0,25 | 1,27 | -3,47 |

| | Alternative 1 | Alternative 2 | Alternative 3 | Alternative 4 | Alternative 5 |
|---|---|---|---|---|---|
| Remedial Action | -0,45 | -0,30 | -0,45 | -0,30 | -0,49 |
| Source Contamination | 3,45 | 3,50 | 3,45 | 3,50 | 3,23 |
| Total Social Score | 3,00 | 3,20 | 3,00 | 3,20 | 2,75 |

| | Alternative 1 | Alternative 2 | Alternative 3 | Alternative 4 | Alternative 5 |
|---|---|---|---|---|---|
| On-Site | 2,12 | 2,12 | 2,15 | 2,15 | -0,56 |
| Off-Site | -1,90 | -0,92 | -1,89 | -0,87 | -2,91 |
| Total Env. Score | 0,23 | 1,21 | 0,25 | 1,27 | -3,47 |

| | Alternative 1 | Alternative 2 | Alternative 3 | Alternative 4 | Alternative 5 |
|---|---|---|---|---|---|
| On-Site | 2,45 | 2,54 | 2,45 | 2,54 | 2,22 |
| Off-Site | 0,55 | 0,67 | 0,55 | 0,67 | 0,53 |
| Total Social Score | 3,00 | 3,20 | 3,00 | 3,20 | 2,75 |

*Figure A 29. Ecological and social effects of the remediation alternatives (scenario 3b).*

# Appendix X – Other Scenarios

- **Boat + Truck Transport VS Truck Transport**

*Table A 13. Input data for scenario +Boat+truck transport VS truck transport.*

| Key criteria | Sub-criteria | Alt.2a | | | Alt.4a | | | Alt.2b | | | Alt.4b | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | R | S | U | R | S | U | R | S | U | R | S | U |
| **E1: Soil** | Ecotoxicological risk RA On-site | NP | -2 | L | NP | -1 | L | NP | -2 | L | NP | -1 | L |
| | Ecotoxicological risk SC On-Site | NN | 10 | L | NN | 10 | M | NN | 10 | L | NN | 10 | M |
| | Soil Functions RA On-Site | NR | | | NR | | | NR | | | NR | | |
| **E2: Physical Impact on Flora and fauna** | Flora and fauna RA On-Site A1 | NR | | | NR | | | NR | | | NR | | |
| **E3: Groundwater** | Groundwater RA On-Site | NP | -2 | L | NP | -1 | L | NP | -2 | L | NP | -1 | L |
| | Groundwater RA Off-Site | NR | | | NR | | | NR | | | NR | | |
| | Groundwater SC On-Site | NN | 10 | L | NN | 10 | M | NN | 10 | L | NN | 10 | M |
| | Groundwater SC Off-Site | NR | | | NR | | | NR | | | NR | | |
| **E4: Surface Water** | Surface Water RA On-Site | NR | | | NR | | | NR | | | NR | | |
| | Surface Water RA Off-Site | NP | -2 | L | NP | -1 | L | NP | -2 | L | NP | -1 | L |
| | Surface Water SC On-Site | NR | | | NR | | | NR | | | NR | | |
| | Surface Water SC Off-Site | NN | 10 | L | NN | 10 | M | NN | 10 | L | NN | 10 | M |
| **E5: Sediment** | Sediment RA On-Site | NR | | | NR | | | NR | | | NR | | |
| | Sediment RA Off-Site | NR | | | NR | | | NR | | | NR | | |
| | Sediment SC On-Site | NR | | | NR | | | NR | | | NR | | |
| | Sediment SC Off-Site | NR | | | NR | | | NR | | | NR | | |
| **E6:Air** | Air RA Off-Site | NP | -4 | M | NP | -4 | M | NP | -5 | M | NP | -5 | M |
| **E7: Non-renewable Natural resources** | Natural Resources RA Off-Site | NP | -2 | L | NP | -2 | M | NP | -2 | L | NP | -2 | M |
| **E8: Non-recyclable Waste Generation** | Waste RA Off-Site | NP | -1 | L | NP | -1 | L | NP | -1 | L | NP | -1 | L |

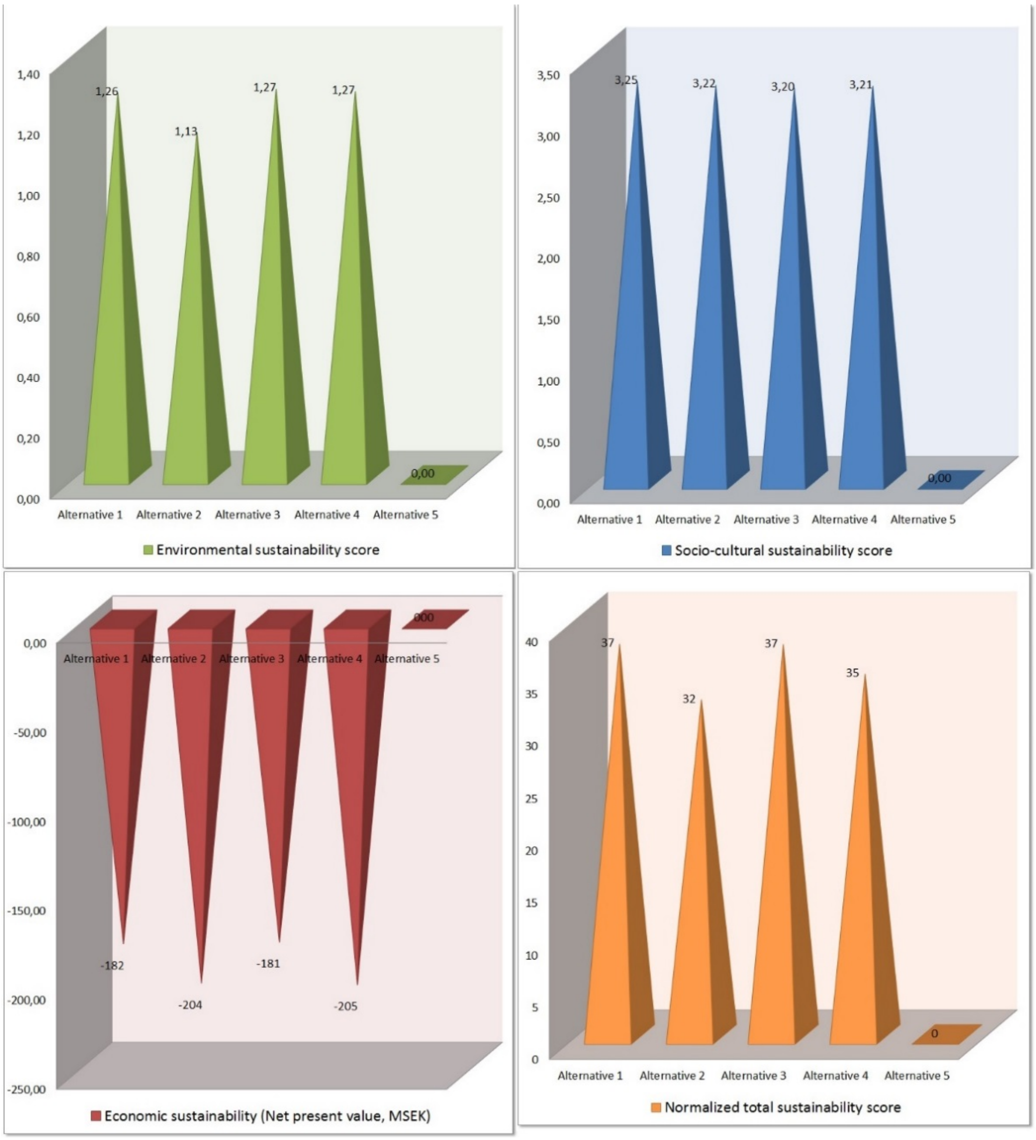
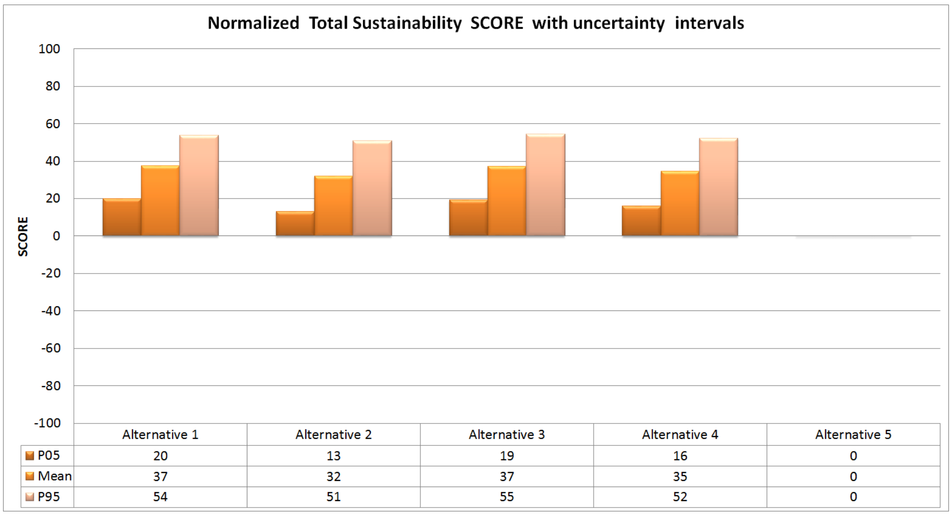


*Figure A 30. Environmental, socio-cultural, economic and total sustainability score of scenario 'boat + truck transport VS truck transport'. Please note that, due to settings in the SCORE model, it was not possible to change the names of the alternative, therefore: alt.1=alt.2a, alt.2=alt.4a, alt3=alt2b, alt.4=alt.4b. There was no fifth alternative in this scenario.*



| | Alternative 1 | Alternative 2 | Alternative 3 | Alternative 4 | Alternative 5 |
|---|---|---|---|---|---|
| P05 | 20 | 13 | 19 | 16 | 0 |
| Mean | 37 | 32 | 37 | 35 | 0 |
| P95 | 54 | 51 | 55 | 52 | 0 |

*Figure A 31. Total sustainability score with uncertainty interval. The problem with the names of the alternatives is present also here.*

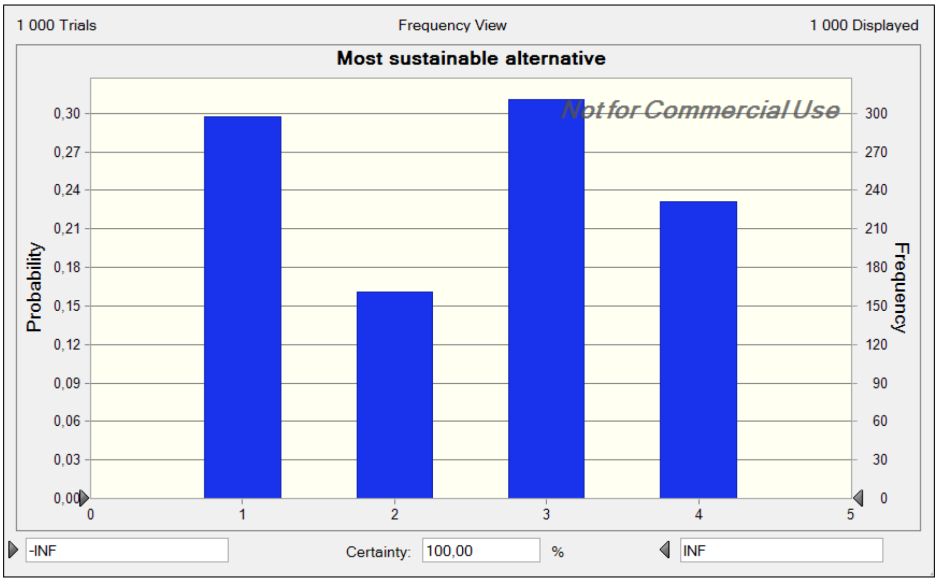


*Figure A 32. Probability of each alternative to be the most sustainable. The problem with the names of the alternatives is present also here.*

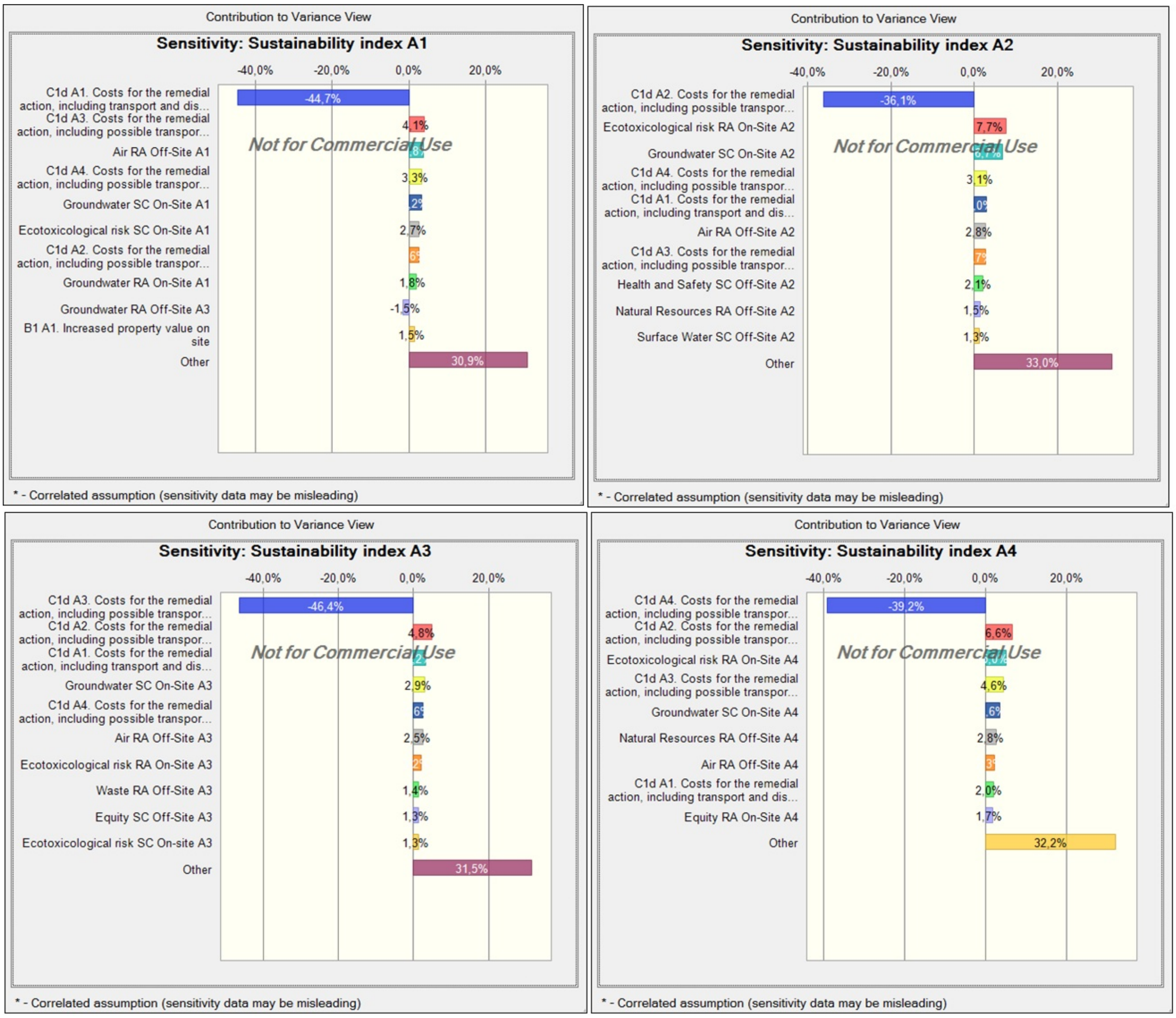


*Figure A 33. Sensitivity analysis for the scenario 'boat + truck transport VS truck transport'. The problem with the names of the alternatives is present also here.*

- **Scenario x**

Scenario x= Scenario Ia with different weighting of the environmental criteria and sub-criteria (as shown in Appendix VIII).

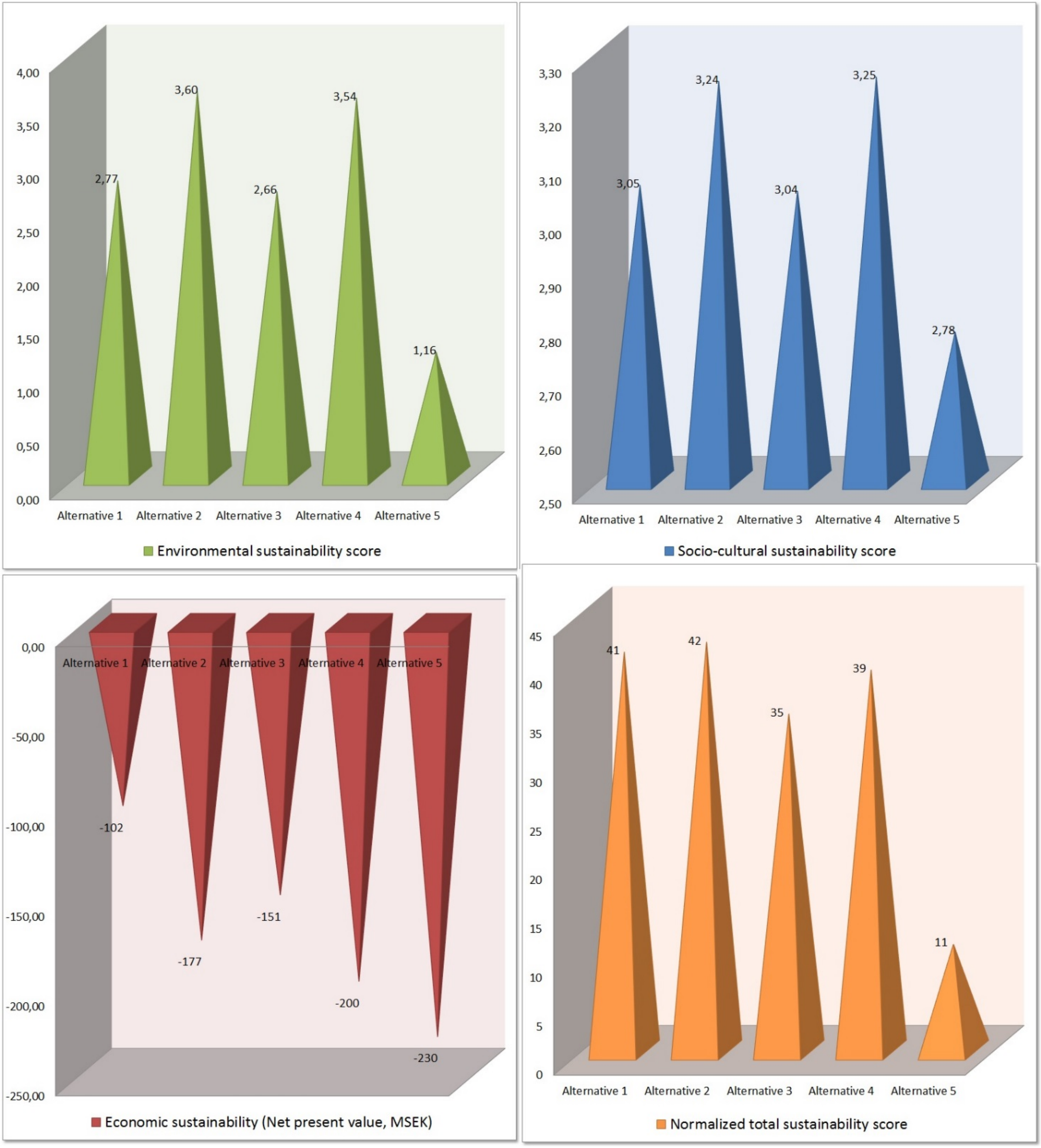
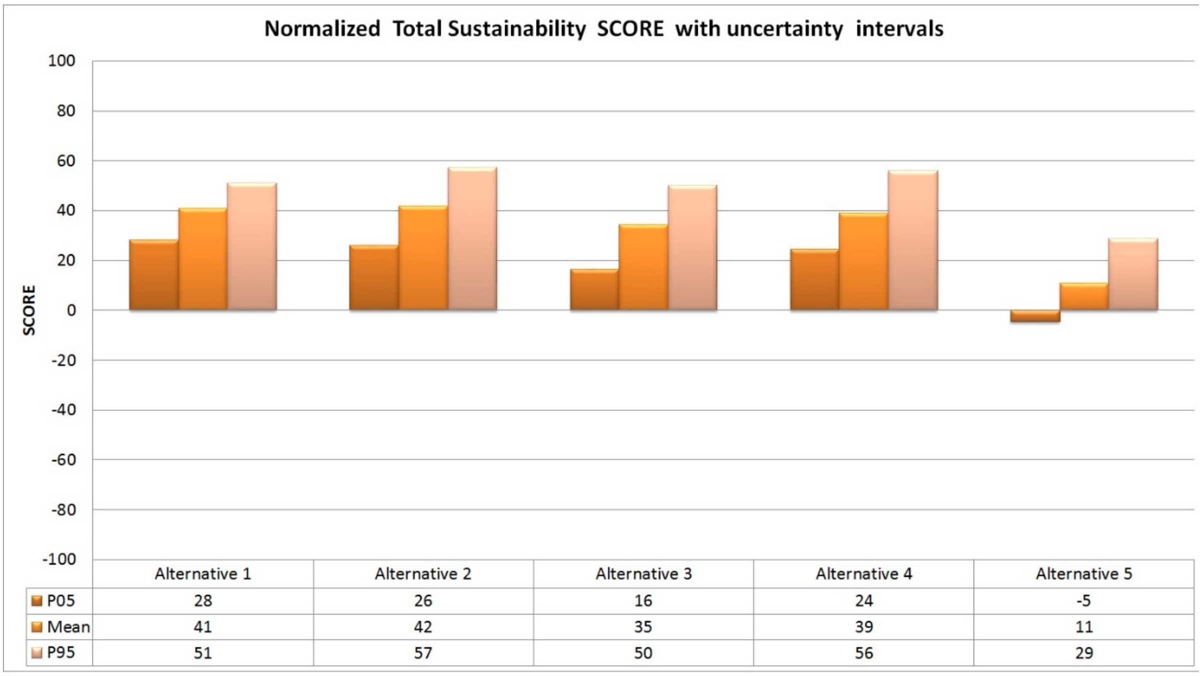
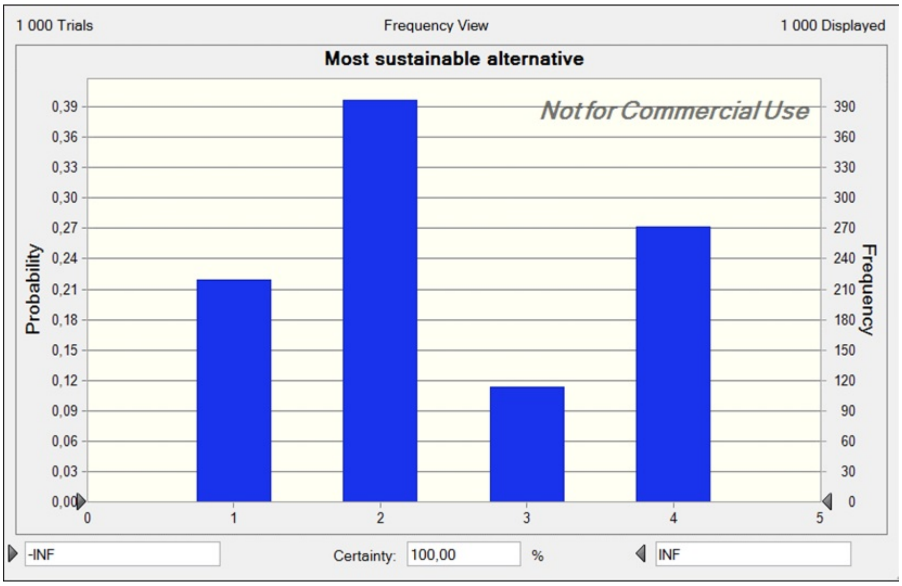


*Figure A 34. Environmental, social, economic and normalized total sustainability scores for scenario x.*



| | Alternative 1 | Alternative 2 | Alternative 3 | Alternative 4 | Alternative 5 |
|---|---|---|---|---|---|
| P05 | 28 | 26 | 16 | 24 | -5 |
| Mean | 41 | 42 | 35 | 39 | 11 |
| P95 | 51 | 57 | 50 | 56 | 29 |

*Figure A 35. Normalized total sustainability scores with uncertainty intervals for scenario x.*



-INF

Certainty: 100,00 %

INF

*Figure A 36. Probability of each alternative to have the highest score in scenario x.*

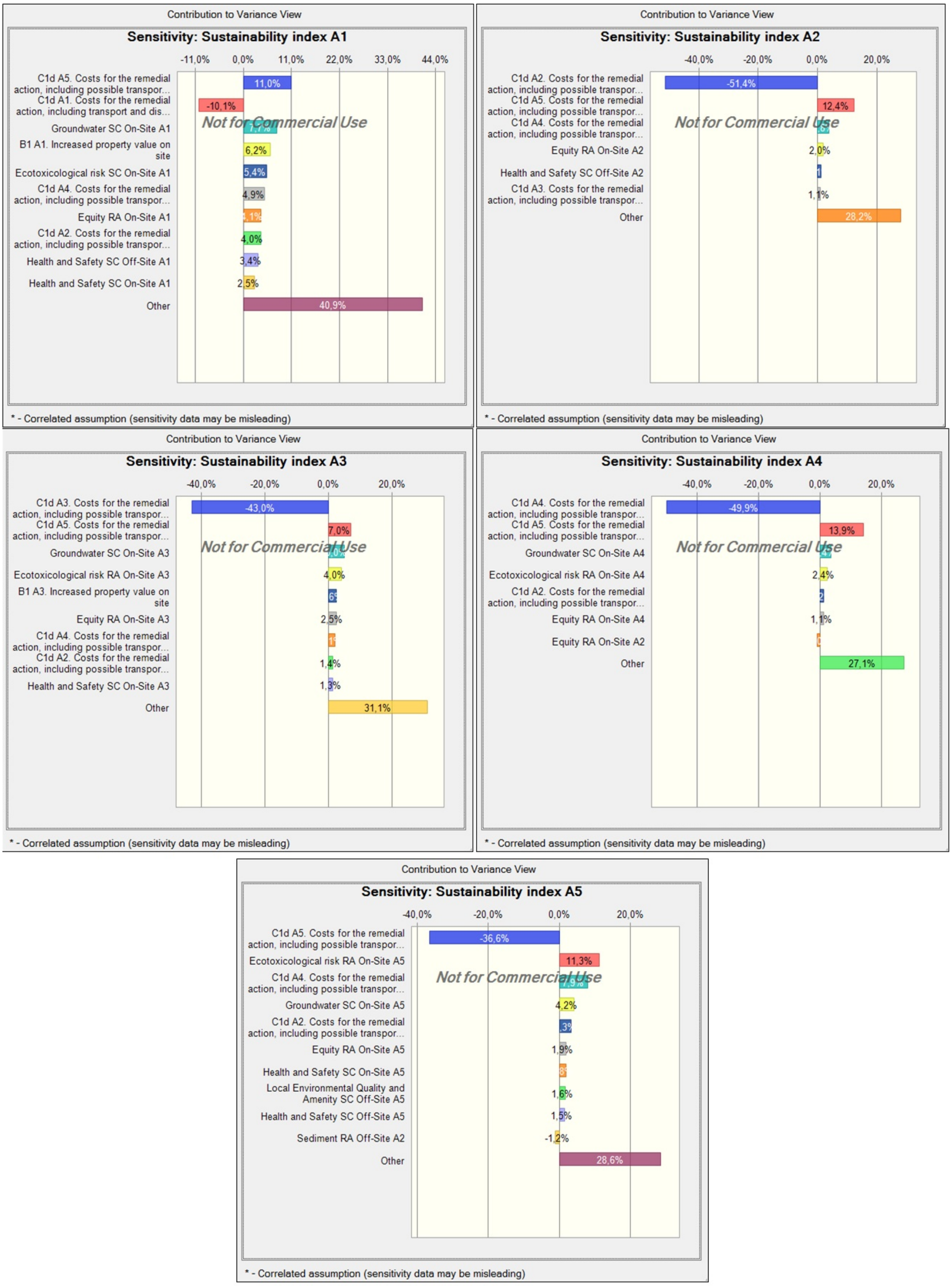


*Figure A 37. Sensitivity analysis of scenario x.*

- **Scenario y**

Scenario y= Scenario Ia with ‘Low’ Uncertainties in the Economic Criteria

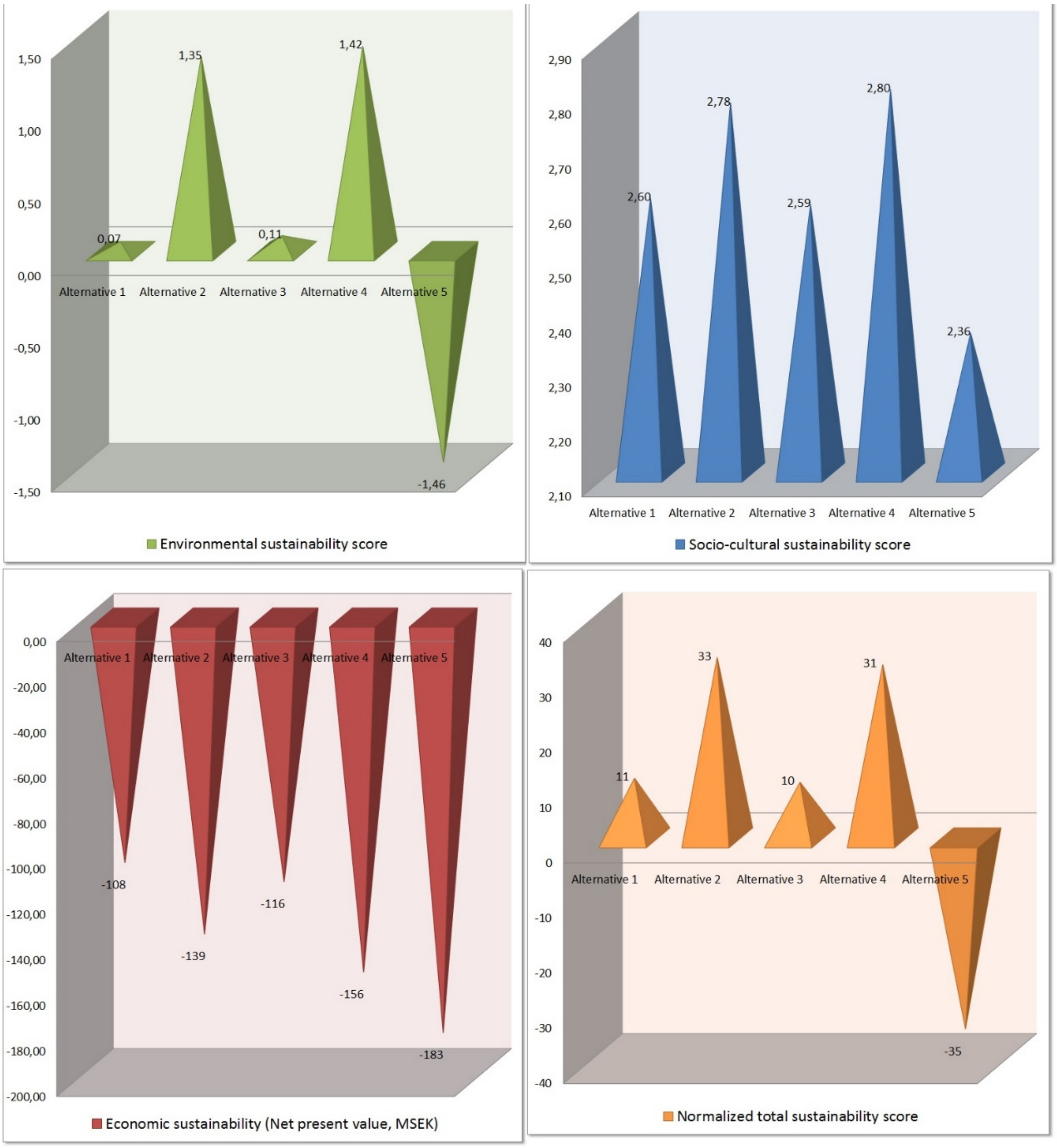
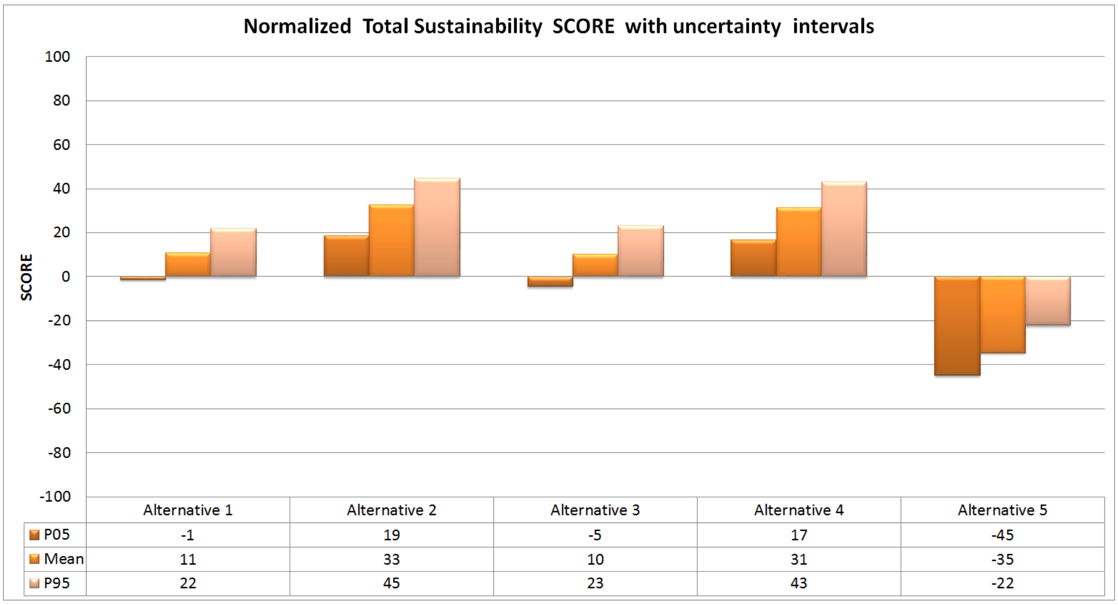
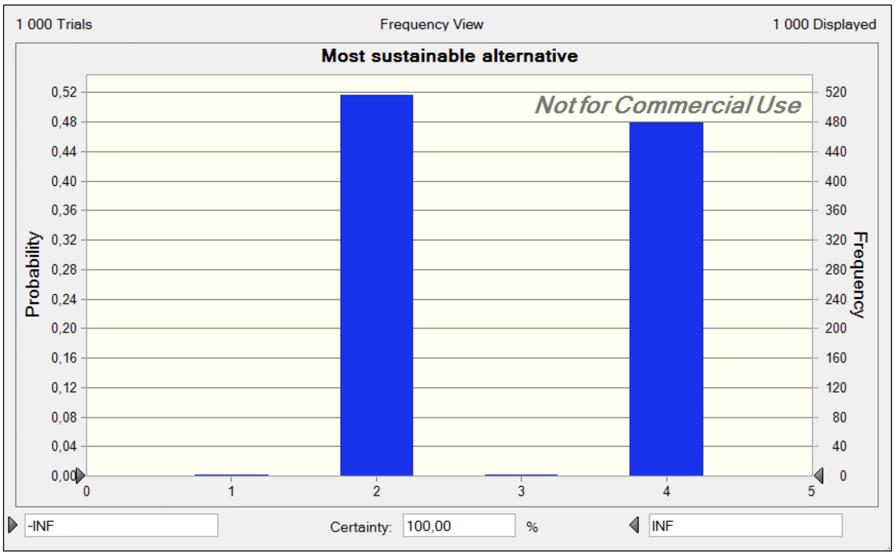


*Figure A 38. Environmental, socio-cultural, economic and total sustainabily scores for scenario y.*



| | Alternative 1 | Alternative 2 | Alternative 3 | Alternative 4 | Alternative 5 |
|---|---|---|---|---|---|
| P05 | -1 | 19 | -5 | 17 | -45 |
| Mean | 11 | 33 | 10 | 31 | -35 |
| P95 | 22 | 45 | 23 | 43 | -22 |

*Figure A 39. Normalized total sustainability scores with uncertainty intervals for scenario y.*



-INF Certainty: 100,00 % INF

*Figure A 40. Probability of each alternative to have the highest score in scenario y.*

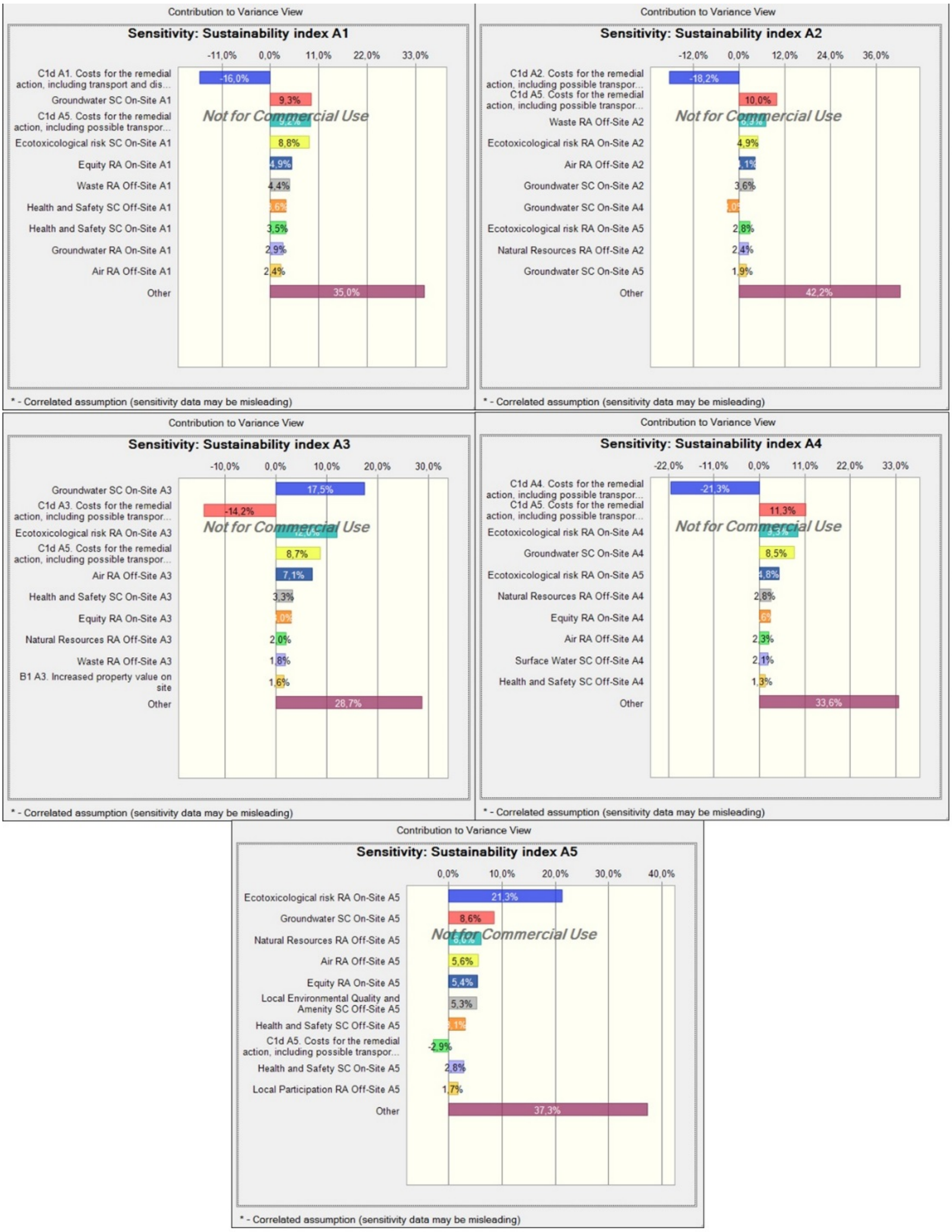


*Figure A 41. Sensitivity analysis of scenario y.*

- **Scenario z**

Scenario z= Scenario Ia with ‘high’ uncertainties assigned to the cost of alternatives 3, 4 and 5.

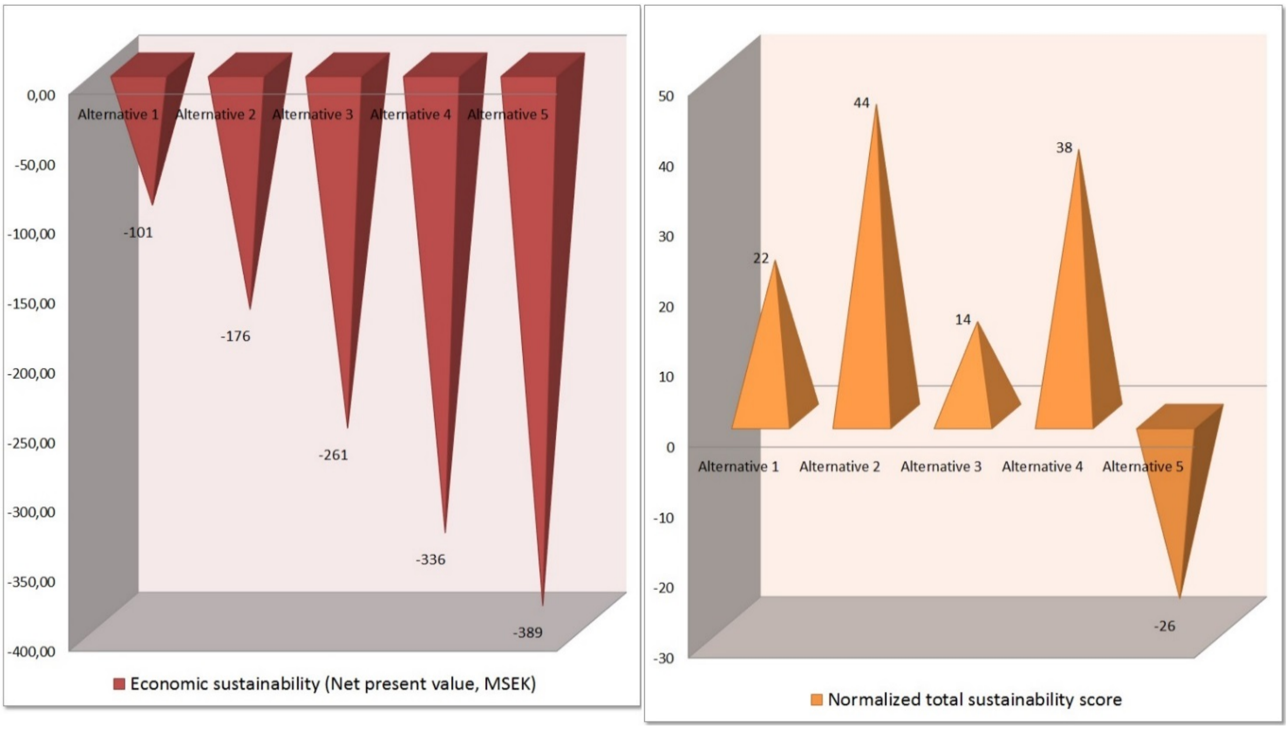
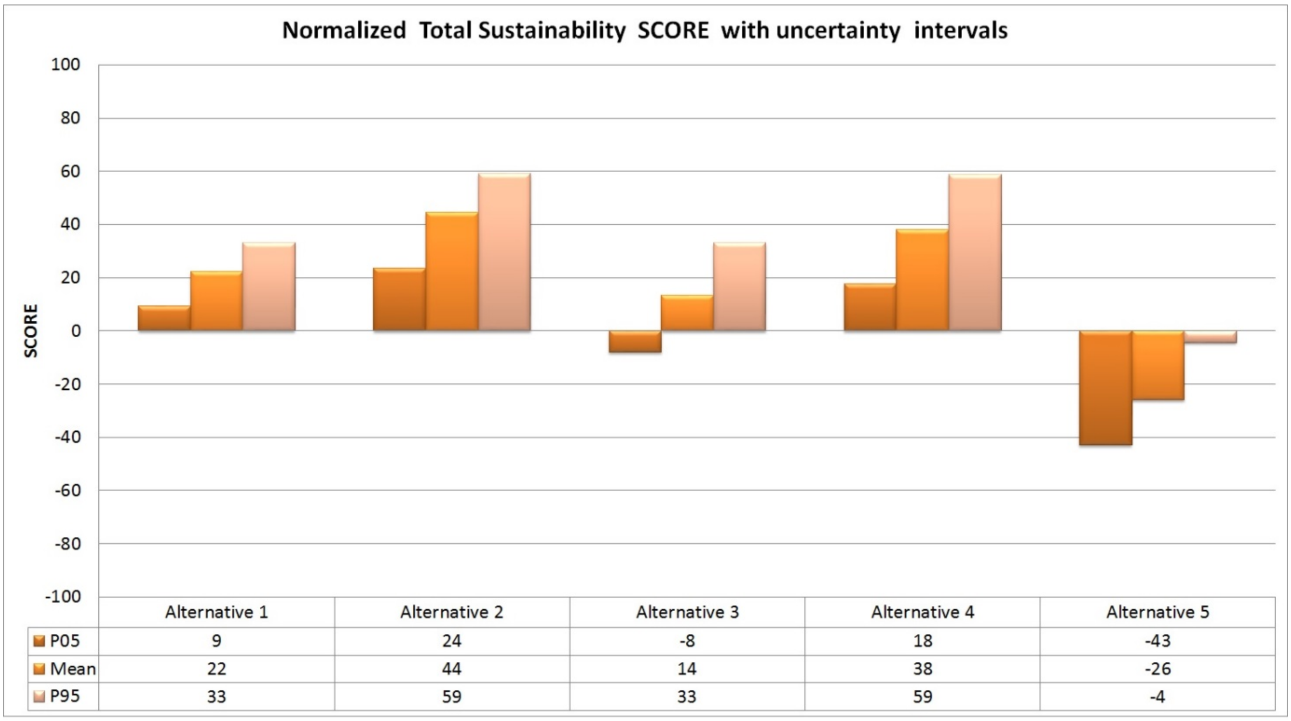


*Figure A 42. Economic and normalized total sustanability scores for scenario z. Environmental and social scores are the same as in scenario Ia.*



| | Alternative 1 | Alternative 2 | Alternative 3 | Alternative 4 | Alternative 5 |
|---|---|---|---|---|---|
| ■ P05 | 9 | 24 | -8 | 18 | -43 |
| ■ Mean | 22 | 44 | 14 | 38 | -26 |
| ■ P95 | 33 | 59 | 33 | 59 | -4 |

*Figure A 43. Normalized total sustainability score with uncertainty intervals for scenario z.*

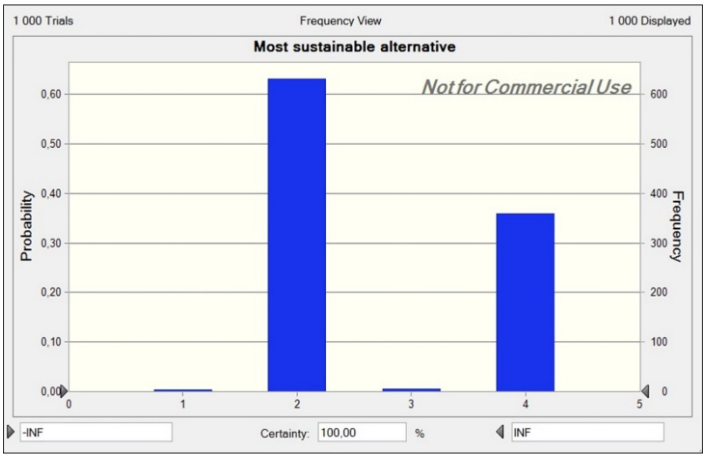


*Figure A 44. Probability of each alternative to score the highest in scenario z.*

*Figure A 45. Sensitivity analysis for scenario z.*