CHALMERS
UNIVERSITY OF TECHNOLOGY

Assessment of Metal Recycling in Remediation Projects

Application and Evaluation of a Cost-Benefit Analysis Method

Master of Science Thesis in the Master's programme Infrastructure and Environmental Engineering

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Department of Civil and Environmental Engineering
Division of Geo Engineering
FRIST Competence Centre
CHALMERS UNIVERSITY OF TECHNOLOGY
Gothenburg, Sweden 2015
Master's Thesis 2015:135

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Examensarbete 2015:135/ Institutionen för bygg- och miljöteknik,
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Cover
Metal contaminated site at Långö, south of Köpmannebro in Mellerud municipality, Västra Götlands County, Sweden. Photo: ttela (2013).

Chalmers Reproservice / Department of Civil and Environmental Engineering
Göteborg, Sweden, 2015

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ABSTRACT

Non-toxic Environment is one of the environmental policy goals in Sweden adopted by the Swedish Parliament in 1999. This means that the environment must be free from non-naturally occurring substances and metals that could threaten human health or biodiversity. A sub-objective of Non-toxic Environment relates to contaminated sites. All polluted land considered as posing acute health risks should be remediated by 2050. Many of these contaminated sites are polluted by metals and the traditional method of remediation is excavation and landfill. However, this is not a sustainable remediation method from the perspective of resource recovery and material cycles. Mining and smelting of virgin ore is the major contributors to the anthropogenic emissions of copper, arsenic and zinc. Recycling of metals alongside with remediation of metals from the contaminated soil can save the world from total extinction of valuable metals like copper. This Master's thesis aims to describe how to evaluate social profitability of metal recycling in combination with the soil washing procedure using a Cost-Benefit Analysis (CBA). The CBA is applied on the former pole impregnation site at Långö, Köpmannebro, the Mellerud municipality. Five different remediation alternatives were evaluated against a reference alternative, i.e. no remedial action is taken. Given the assumptions made in this study, the CBA results show that none of alternatives has a positive net present value (NPV) at different discount rates of 3.5%, 1.4% and 0% respectively. Meanwhile, it was assumed no benefits associated with *increase in land value* (B1) after remediation due to the site location. Furthermore, the study shows that from a purely economic perspective it is not worthwhile to recycle metals from contaminated soil in remediation. But, if recycling should be done, *Alternative 2* which assumes excavation and direct landfilling of the soil, and excavation and incineration of bark and peat, followed by ash washing and metal sludge sale to a mining and smelting company is the best recycling alternative. However, the CBA results can be different if transportation distances to incineration and washing facilities were minimized. The economic values for an improvement in ecosystem services on the site after remediation was estimated using a benefit transfer method. A sensitivity analysis conducted with Monte Carlo simulation shows that some benefit and cost items have insignificant effects in the analysis. Moreover, it was not possible to monetize some benefits in this study. These benefits are most likely to contribute to a significant degree of variation than what the statistical net present value distributions have shown in this analysis. However, CBA is a valuable method that can be used as a decision-support tool prioritizing between the remediation alternatives in the projects assuming metal recycling.

Key words: Cost-Benefit Analysis, Långö -Köpmannebro, remediation, contaminated soil, benefit transfer, discount rate, Monte Carlo simulation.

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Contents

Preface and acknowledgements

This Master's thesis was carried out within the Department of Civil and Environmental Engineering at Chalmers University of Technology, Sweden. The study assesses possible remediation alternatives for a metal polluted site in Sweden using cost-benefit analysis method.

I wish to thank my supervisors, Dr Yevheniya Volchko and Associate Professor Karin Karlfeldt Fedje for your continuous support and interest in my work. I am sincerely grateful to Associate Professor Jenny Norrman for the kind support rendered to me during my work. Also, I would like to thank my examiner Professor Lars Rosén for his comments and valuable guidance on my thesis. I also appreciate his acknowledgement of this thesis contributions to remediation field.

Many thanks to my family for your never ending encouragement and support. A special thanks to my husband Adetayo and my adorable sons Abdrahman and Abdraheem, your warm hugs and smiles make me realize how beautiful my life is.
I love you.

Göteborg, August 2015

Abibat Adedigba

1. Introduction

This chapter briefly presents the context of the thesis by providing the background to environmental goals concerning contaminated sites in Sweden. It provides short discussion on environmental impacts of mining and metal recycling, defining the aim of this Master's thesis and limitations.

1.1 Background

In 1999 the Swedish Parliament adopted environmental policy goal with a number of environmental objectives to promote environmentally sustainable development. "*The overall goal of Sweden environmental policy is to hand over to the next generation a society in which the major environmental problems have been solved, without increasing environmental and health problems outside Sweden's borders*" (Swedish EPA, 2012). One of these environmental objectives is *Non-toxic Environment* which means that the environment must be free from non-naturally occurring substances and metals that could threaten human health or biodiversity. The non-toxic environment objective has nine sub-objectives of which one is on contaminated sites and this sub-objectives states that all contaminated sites that are considered as posing acute health risks should be remediated by 2050 (Swedish EPA, 2013). In Sweden approximately 80 000 sites have been identified as potentially contaminated. Heavy metals and organic pollutants are often source of contamination on these sites.

Långö in the Mellerud municipality is one of the Swedish sites which is polluted with heavy metals, mainly copper. It was a telegraphy pole impregnation site in the earlier nineteen century, whereby copper sulphate was used as a wood preservative. The level of the contaminants in the soil had left the site barrel with no vegetation and abandoned. The most common remediation action in Sweden is to excavate and landfill contaminated masses, which is usually called "Dig and Dump" (D&D) and is not considered as the most sustainable method of remediation. Research has been carried out on soil washing combined with metal recycling as an alternative method to remediate sites contaminated with metals (Karlfeldt Fedje et al., 2013). Enhanced soil washing using acidic process waters from solid waste incineration is considered as being more sustainable method for remediation of the soil polluted with heavy metals. The leachate generated from soil washing is rich in metals and can act as a source for metal recovery. This approach had been carried out in a lab scale experiments. The results show that more than 90% metals in the leachate can be recovered. However, this is just a small scale experiment and it is difficult to predict how cost-effective would the soil washing procedure be when it was applied to large scales, i.e. tons of contaminated masses.

1.2 Environmental impacts of metal mining

Mining is a long time practice of accessing natural resources. It is historically regarded as the starting point for a series of economic and social changes that constitute development in countries like Australia, Canada, Sweden and United States (Bridge, 2004). The world Resource Institute indicated in the report from 2004 that 75% of the active mine globally overlap with areas of high conservation value and highly stressed basins. Furthermore, more than 25% of the mining sites are within or at a radius of 10km from protected areas and three quarters of the active mining sites are located within ecosystems intact of a high conservation value (WRI, 2004). Mining has been generating a great many of environmental problems which (*i*) stem from waste management and anthropogenic emissions, and (*ii*) lead to natural and human health hazards. The waste produced in mining is so enormous that over 99.5% of the material mined to produce virgin copper is referred to as waste. Disposal of this waste is not properly managed by the mining companies, leading to degradation of natural habitat (Bridge, 2004). The impact of mining on biodiversity and ecosystem has been of great concerns globally. Mining itself can cause natural hazard such as earthquakes and flooding and various human health problems are associated with mining. The mining and smelting of ore are the major contributors to the anthropogenic emissions of copper, arsenic and zinc (Bridge, 2004). The environmental impacts of mining in many countries are disproportionately large, the negative impacts overweight the positive impacts and contribution of mining to sustainable development is very poor in the global perspective (WRI, 2004).

1.3 Metal recycling

The world natural reserve of some metals like chrome, copper and zink is moving close to exhaustion and predictions show that these metals will no longer exist in their natural endowment after the next 15, 40 and 20 years respectively (Karlfeldt Fedje et al., 2013). There is a possibility of an increase in the metal prices in the near future, as the global population continues to rise so the demand for finite virgin metal will increase. Recycling of metals alongside with the remediation of metals from contaminated soil can save the world from total extinction of valuable metals like copper. In Europe, about two million sites are identified as potentially polluted and 50 percent of these sites are polluted with metals (Karlfeldt Fedje et al., 2013). Recycling of metals can serve as a better alternative to remediate contaminated soil instead of the conventional method which is excavation and landfill. The latter is not solving the problem rather than just transferring the problem to another site, also metal is being remove from the material cycle, resulting in the loss of valuable resources. Recycling can also help to reduce the amount of pollutant that eventually will be seeping from landfills into the groundwater. Metals in the contaminated soil can be recycled using many different methods. One of the promising methods is a soil washing method. Soil washing is a treatment technology that uses liquid such like waste process water from waste refinery to remove hazardous contaminants from soil. The method is more extensively used in Europe than in USA. It has been proving to be a useable remediation method in Sweden (Karlfeldt Fedje et al., 2013; WR-58, 2013). The leachate from washing the contaminated soil is rich in metals and can act as a source for metal recovery. The metal content in the leachate can be extracted through bio electrochemical systems or chemical precipitation (Karlfeldt Fedje, 2015) [1]. Metal recycling from contaminated soil has not been proving economically viable (Karlfeldt Fedje et al., 2013) but doing so will reduce the environmental problems associated with mining natural ore.

[1] Karin Karlfeldt Fedje, associate professor lecture, Chalmers University. 2015-06-04

1.4 Aim and scope

The overall aim of this Master's thesis is to describe how to evaluate social profitability of metal recycling in combination with the soil washing procedure as an alternative remediation method.

The objectives are (1) to assess metal recycling in the Långö remediation project using Cost-Benefit Analysis (CBA), and (2) to evaluate applicability of the CBA method developed by Rosén et al. (2008) and Söderqvist et al. (2015).

This thesis is carried out within the scope of the project "Soil Washing and Recovery of Copper and Chromium from Highly Contaminated Soils"[2]. The earlier research studies by Karin Karlfeldt Fedje on soil washing and copper recycling from contaminated sites and by Yevheniya Volchko on Cost-Benefit Analysis of copper recycling in the Långö remediation project have formed the point of departure in this study. The spreadsheet models with preliminary calculations of costs and benefits associated with metal recycling at the Långö site served as input for this Master's thesis.

1.5 Limitations

This Master's thesis tests the CBA method only on one case study with five remediation alternatives relative to the reference alternative, i.e. no remedial action is taken. To achieve a representative basis for conclusions about a metal recycling project in combination with remediation, more than one case study is preferable. The assessment does not include the cost of purchasing or renting the equipment for soil washing and project risks. Only chemical precipitation of metals from metal rich leachate is investigated, whereas, to give a complete assessment on metal recycling from metal rich leachate using bio electrochemical systems should also be investigated.

[2] https://www.chalmers.se/en/projects/Pages/Soil-Wasing-and-Recovery-of-Copper-and-Chromium-from-Highly-Contaminated-Soils.aspx

2. Theory and Literature Review

2.1 Cost-Benefit Analysis for Environmental Projects

Cost-Benefit Analysis (CBA) is a tool that has been extensively used for a long time. It is a technique that is commonly used to measure all the benefits and costs of a project from the social perspective view and the result of the measure is convey to by the decision makers (Hanley & Barbier, 2009). The origin of CBA can be dated back to the beginning of nineteenth century where it was used for infrastructure appraisal in France in the 1920s and as an appraisal in the new dam construction scheme in U.S.A in the late 1930s. CBA is recognised as the major appraisal technique for both public policy and investments. Theoretically, CBA is used to calculate public welfare, defining benefits as increase in human well-being and costs as reduction in human well-being (Pearce et.at, 2006). In this context, CBA can be defined as a process of analysing proposed or previously enacted projects by quantifying the costs and benefits of a project or project alternatives over a certain period of time, in order to determine whether doing the project is in the public interest and makes financial sense. It is an essential tool for estimating the economic benefits of projects where all project impacts, e.g. economic, social and environmental, are assessed in monetary terms to conclude whether the project is worth implementing or not (EC, 2006). CBA is used both in the developed and developing countries and in Sweden for analysing societal profitability of various governmental projects, but the use of CBA is limited in Swedish environmental projects, such as in the remediation of contaminated soil (Rosén et al., 2008).

Monetization of the benefits and costs of goods and services that are not traded on the market are usually a difficult task to accomplish. The valuations of environmental resources is usually carried out either by a direct or indirect methods. The direct method is also referred to as stated preference (SP) model. It uses surveys to ask individuals' valuations for hypothetical changes in environmental resources. Example of state preference are *Contingent Valuation* (CV) and *Choice Experiment* (CE). Indirect method also known as *Revealed Preference* (RP) model that relies on the behaviour of individuals in related markets to reveal their valuations of the non- marketed goods. Examples of RP models are *Travel Cost* model and *Hedonic Pricing* model (Garrod & Willis, 1999). The most important part of CBA is to discount all the identified costs and benefits of the project and estimate the net present value (NPV). Discounting is a term in welfare economics that refers to the process of assigning value to the future costs and benefits of a project, using a designed social discount rate. Doing this indicates whether the sum discounted benefits is greater or less than the sum of the discounted costs and tell if the project represent an efficient shift in resource allocation (Hanley& Barbier, 2009). The difficulty of quantifying and valuing all impacts of environmental projects is coupled to the lack of functioning markets for the majority of environmental goods. This issue leads to uncertainty in CBA method for environmental projects. Therefore, it is very important to include uncertainty and sensitivity analysis in CBA in order to show how the NPV of project changes with different discount rate (Hanley& Barbier, 2009).

To carry out a CBA requires a logical sequence of steps to achieve a well-executed assessment (Pearce et.at, 2006). Rosén et al. (2008) developed a CBA method for remediation projects which includes concrete examples of the costs and benefits that commonly associated with remediation. It elaborates the process of prioritizing choice amongst remediation alternatives in an effective way, by comparing the benefits and costs of a number of remediation alternatives with a reference alternative. The methods is generally described in four steps as illustrated in Figure 2.1

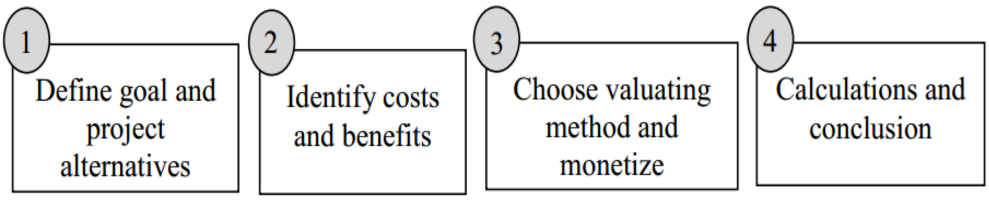

Figure 2.1. Flow chart for the cost-benefit analysis (after Rosén et al., 2008, Landström & Östlund, 2011).

Step1. A well-defined goals and project alternatives that including the reference-alternative is the first important step in CBA of remediation projects.

Step 2. Söderqvist et al., (2015) identified concrete costs and benefits associated with remediation projects. Both the costs and benefits are divided into main and sub-item categories, as shown in Table 2.1 below.

Table 2.1. Benefits (B) and costs (C) items and sub-items related to remediation action (Söderqvist et al., 2015, Brinkhoff, 2014).

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

Step 3. Rosén et al. (2008) recommend to use *Contingent Valuation* (CV) method as one of the valuation methods for identifying public's willingness to pay for a certain environmental improvement. Another possible method could be the *Hedonic Pricing* which uses the connection between a good/service and its characteristics to calculate the monetary value when quantifying the identified costs and benefits items.

Step 4 Evaluate the Net Present Value (NPV) of the monetized discounted values of all costs and benefits.

Concluding, the application of CBA to environmental issues is always loaded with problems due to the intrinsic value about nature and uncertainty surrounding appropriate discounting and discount rate to apply (Hanley et.al., 1993). CBA should not be seen as a sufficient single criterion but it should be complemented with other types of assessment to achieve a more reliable objective for decision-making (Söderqvist et al., 2015).

The described method was further operationalized with the Excel-based SCORE tool (Rosén et al., 2015) which includes a CBA tool (Söderqvist et al., 2015).

2.2 Net Present Value

Net Present Value (NPV) is one of performance indicators to determine the social-profitability of the project. It is calculated according to Eq. 1:

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

Where

$Bt = (B1_t + B2_t + B3_t + B4_t + B5_t)$; Benefits [SEK] at time *t*,

$Ct = (C1_t + C2_t + C3_t + C4_t)$; Costs [SEK] at time *t*,

r_t = discount rate at time t,

T = time horizon associated with the benefits and costs.

The result of the NPV is interpreted as

NPV < 0 indicates a negative social profitability, and

NPV > 0 indicates a positive social profitability.

In principle, if the Net Present Value of a project is positive, then the project is socially profitable.

2.3 Willingness-To-Pay assessment using Benefit Transfer for improved groundwater quality

Improvement in the methods for valuation of non-market goods and services is a major concern in cost-benefit analysis (Pearce et al., 2006). A technique that can provide decision makers with a cost-effective and efficient monetary valuation of non-marketable goods and services is required. One major technique that was developed to be an effective method for valuation of non-market goods and services in a project or policies is *Benefit Transfer*. Benefit transfer is extrapolation of the existing information designed on the non-market value of goods and services from one specific context into another context (Hanley & Barbier, 2009). This method has been used in the U.S.A since 1930. The transfer can be related to benefit or cost with adjustment of the environmental characteristics, differences between the new sites (also referred to as *policy site*) to which the value is transferred and the original site (also referred to as *study site*) for which the value was assessed (Pearce et al., 2006, Hanley & Barbier, 2009). For example, using results from previous valuation studies on changes in water quality in one or more other areas (*study areas*) can be used to estimate the value of the proposed water quality improvement in another area (*policy area*). A benefit transfer is basically a way to avoid performing time-consuming and costly primary studies for a new environmental improvement site (Enveco, 2014).

When using benefit transfer, it is very important to assure similarities in environmental conditions and adjust differences between the policy site and the study site, e.g. income of interviewees, in order to attain a satisfactory and cost-effective economic valuation of the new site. There is a lot of uncertainty surrounding benefit transfer and it is fundamentally impossible to determine exactly how much uncertainty is involved in the technique. This implies that it is practically impossible to determine how large the potential value transferring error ("transfer error") when using this method. Most literature on benefit transfer usually assumes transfer error between 25-40% (Enveco, 2014). It is possible to validate benefit transfer only if primary data is available for the policy site.

There are basically two approaches to benefit transfer, *unit transfer* and *function transfer*. Both methods measure the consumer surplus by estimating alternative average or the median of willingness-to-pay (WTP) per person or household/ month or year from the total number of the affected population. The average WTP is the correct welfare measure to use in WTP studies, but sometimes the median value is used as a more conservative measure. Similarly, the WTP per household, rather than per individual, and WTP per year, instead of a month are more conservative measures. The steps to follow when using benefit transfer vary from author to author. However, the bottom line is that benefit transfer between projects is reasonable as long as the countries involved in valuation have the same guidelines, with similar income levels and cultural conditions. An extreme caution should also be taken when transferring value from studies that are older than ten years (Kriström & Bonta Bergman, 2014).

2.4 Uncertainty and Sensitivity Analyses

Economic assessment and quantification of benefits and costs in environmental projects will always be associated with some uncertainty. This implies that all the effects of the remediation alternatives can never be measured exactly. The uncertainty results from lack-of knowledge (epistemic uncertainty) and natural variability (aleatory uncertainty) (Rosén et al., 2013). The epistemic uncertainty can be reduced, at least in principle, but aleatory uncertainty cannot because of the inherent randomness in nature. Therefore it is recommended to make a sensitivity analysis for all the discounted variables or parameters in order to identify the most uncertain variable and how it affects the CBA result. It is very important to conduct the sensitivity analysis in a statistical simulation where uncertain variables and parameter are described with a statistical distribution. The conventional simulation method for uncertainty and sensitivity analysis is Monte Carlo simulation (Rosén et al., 2008). Monte Carlo simulation is an earlier and common approach to analysis of uncertainties and sensitivity in environmental issues (Burgman, 2005). A Monte Carlo stimulation analysis operates with random input variables and the uncertainties in the input variables of the model are described with statistical distribution. There are different types of statistical distribution in a Monte Carlo stimulation MS Excel add-in Oracle™ Crystal Ball. Triangular, lognormal, normal and discrete uniform distributions are examples of some common statistical distributions in Oracle™ Crystal Ball (Figure 2.2).

Each distribution is described with different parameters. For example, the triangular distribution accommodates a lower bound (minimum value), a central tendency (likeliest) and an upper bound (maximum value) for a variable of the model forming a triangular distribution. It is a popular distribution because of its simplicity in definition and flexibility in shape. However, it can generate biases for skewed data, especially, when the maximum value is too large making the distribution to skew to right and resulting into large estimates for the mean. Triangular distribution has no theoretical basis. It is only based on expert judgement or assumption (Burgman, 2005). The lognormal distribution is a frequent choice for quantities that are positive and right skewed. Its parameters are mean and standard deviation. Three conditions form lognormal distribution: (1) the uncertain variable can increase without an upper boundary, but confined to a finite lower value; (2) the uncertain variable shows a positively skewed distribution; and (3) the natural logarithm of the uncertain variables gives a normal curve. (Oracle, 2009). The normal distribution is the most important distribution in probability theory due to capability to describe many natural phenomena. Its parameters are mean and standard deviation. The conditions for normal distribution are: mean value is the most likely value, it is symmetrical about the mean, and distribution is more likely to be close to the mean (Oracle, 2009). The discrete uniform distribution is described with minimum and maximum values only. In this distribution the minimum and maximum values are fixed and all values between them occur with equal probability (Burgman, 2005).

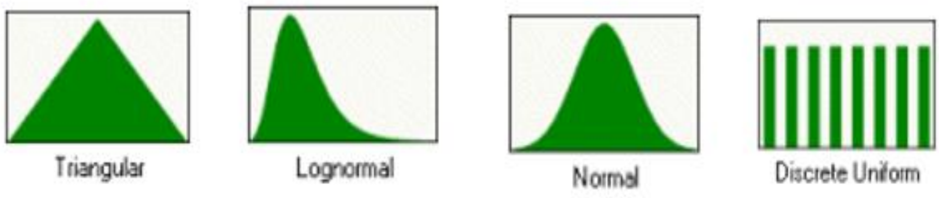

Figure 2.2. The triangular, lognormal, normal and discrete uniform statistical distribution (Oracle Crystal Ball User's Guide, 2009).

When a preferable statistical distributions have been chosen for variables in the model, the Monte Carlo simulation runs a number of trials making up a forecast of uncertainty in the result, as schematically illustrated in Figure 2.3. Simulation can be performed up 10 000 times (Burgman, 2005).

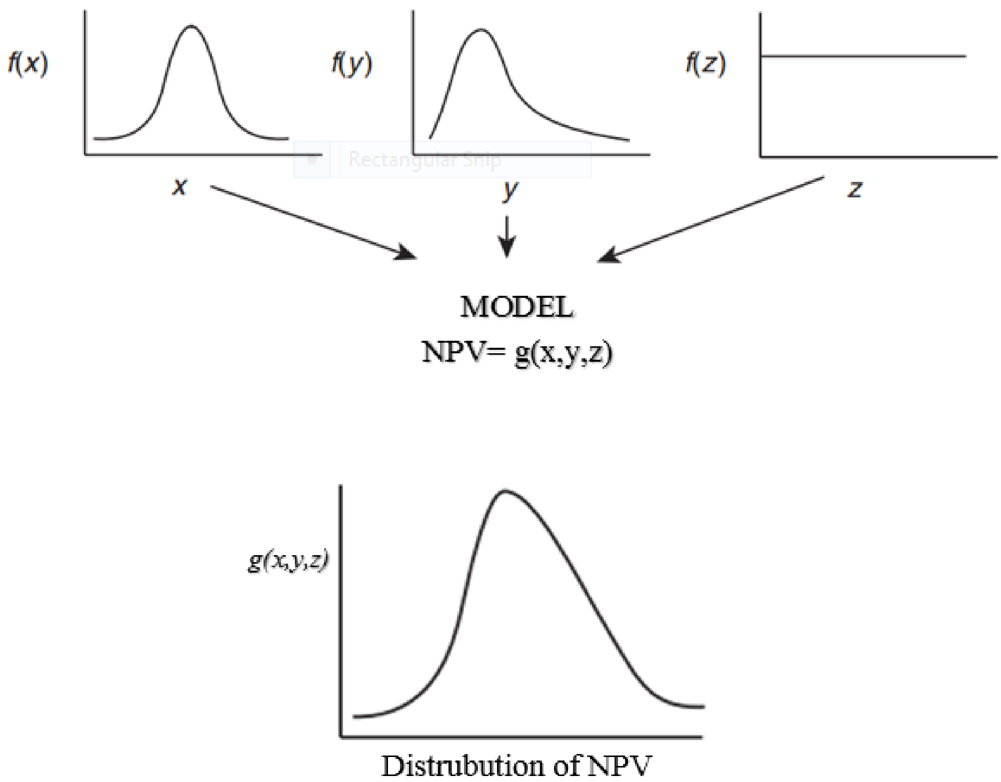

Figure 2.3. Schematic representation of the combination of uncertain variable of normal, lognormal and uniform distribution, using Monte Carlo simulation (after Suter, 1993; Burgman, 2005).

3. The Långö Case Study Site

3.1 History of the site

The site is located on Långö, south of Köpmannebro in the Mellerud municipality, Västra Götlands County, Sweden. In the 1900s, the site was used by Kungliga Telegrafstyrelsen, a Swedish government agency for telecommunication to manufacture impregnated telegraph poles. According to Kemakta (2012), the plant used copper sulphate as a preservative agent to impregnate logs through a process called the Boucherie method. Through this method, copper sulphate solution was pressed into the logs with the bark attached and the logs were allowed to drip all the solution out. After the liquid stopped dripping, the bark was peeled off from the logs and left on the ground. The bark contains high levels of copper and moderate levels of lead. The peeled bark was not taken care of leading to contamination of 8000 m^2 at the Långö site.

The Långö site consists of large exposed rock in North-South direction of the area with massive of bark deposition on the site. The soil layers consist of peat, clay and glacial till, the last two are referred to as mineral soil (Kemakta, 2012). The entire area is surrounded by water and natural area. Lake "Dalsjön" and the up-stream outlet for Lake Vänern are situated in West and North respectively. In East and South Långö is covered by forest used as private properties for holiday living. The South part is a relatively wooded flat ground with some small bogs (Kemakta, 2012). Today the site cannot be reached by vehicle, however, it can be reached by boat. There is also a railway line running through the site, connecting Gothenburg and Karlstad. The main study on Långö site by Kemakta, (2012) indicated concentrations of copper in the bark, peat, clay and glacial till equal to 13 700mg/kg, 18 300mg/kg, 1 800mg/kg, and 4 500mg/kg respectively. The total amount of copper that is embedded in the soil and bark is approximately 35 tons (Kemakta, 2012). Figure 3.1 below present overview of the Långö site.

Figure 3.1. Långö contaminated site, Köpmannebro (Eriksson & Johansson, 2013).

3.2 Reference alternative

In CBA, it is recommended to define a reference alternative in order to be able to compare different remedial actions (Rosén et al. (2008). The reference alternative in the Längö case assumes no remedial action and demands for restrictions on land use (Kemakta, 2012).

3.3 Remediation goals

The overall remediation goals set for the Långö metal contaminated site according to Kemakta, (2012) are described as follows:

1. Vegetation will be re-established within the area previously used for pole impregnation.
2. The area will be used for recreation without the risk of adverse health effects caused by contact with contaminants.
3. It should be possible to pick any mushrooms and berries that may grow in the area.
4. Drinking water quality in nearby drilled wells and the groundwater quality in the area as a whole will improve with time.
5. The conditions for biological life in adjacent waters should be maintained.

3.4 Remediation alternatives

The possible alternative ways to remediate contaminated site at Långö, Köpmannebro were developed by Karin Karlfeldt Fedje[3], Yevheniya Volchko[4] and Lars Rosén[5] (Chalmers), and further refined in this study with regard to transportation distances and amounts based on earlier research and available consultation reports by Kemakta AB (Kemakta, 2012) and Elander Miljöteknik AB (Elander, 2014). In this study a total of five remediation alternatives are considered (see details in Sections 3.3.1-3.3.5). To fulfil remediation goals, all remediation alternatives assume excavation of contaminated masses, transportation of bark and peat to incineration facility, landfilling and refilling of the site with clean material and topsoil to facilitate the reestablishment of vegetation on the site. Soil and ash washing is considered in *Alternatives 2, 3* and *5* as a process towards recycling of copper content in the ash and soil before being landfilled. In *Alternative 1* the excavated material will only be incinerated and the ash will be landfilled. While in *Alternative 4* bark and peat are incinerated and the ash is sold and transported to a mining company. Transportation by boat and truck is chosen for all the alternatives. Transportation by boat is mainly due to fact that Solør Bioenergi Svenljunga AB (Svenljunga värmeverk) situated in Elmogränd Svenlunga is the only plant in Sweden that can incinerate bark and peat from Långö separately from other waste (Elander, 2014). Solør Bioenergi Svenljunga AB has an interim storage facility in Trollhättan and transportation by boat is the most accessible route to Trollhättan from the, Köpmannebro site (Elander, 2014).

Remediation activities require a space for loading of the contaminated masses and off-loading of refilling materials. For this purpose a barge attach to a ramp or conveyor can be arranged in close proximity to the contaminated area instead of constructing a quay for loading as suggested in Kemakta (2012). At the cape of the Lake, shore power assess could be arranged with the help of a shallow draft pontoon with outriggers that will connect a loading ramp or conveyor to land. This eliminates the need for dredging on the sea side and also further contamination of water because the sediment in around water area are as well contaminated.

In each remediation alternative a total of 9 470 tons will be excavated and a total of 16 000 tons of refilling material is needed (Elander, 2014). Bark and peat are incinerated together due to high organic carbon content present. It is not permitted to landfill such contaminated masses directly according to the Swedish Environmental Law. Incineration of bark and peat will also optimise a washing process in order to increase the potential copper release (Karlfeldt Fedje et al., 2013). The ash content in the bark varies between 1-6% and peat can vary from about 3-10%, but Swedish nationwide acceptable number for ash content in peat is 4.3% of it dry matter (Bränslehandboken, 2012). In this study, it is assumed the loss on ignition for bark and peat to be 94% and 95.7% respectively.

It is very important to note that the amounts of each contaminated medium that will be excavated from the Långö site are in wet weight. The amount of bark and peat that will

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[3] Karin karlfeldt Fedje, Associate Professor. Chalmers University of Technology, Sweden
[4] Yevheniya Volchko,PhD. Chalmers University of Technology, Sweden
[5] Lars Rosén, Professor. Chalmers University of Technology, Sweden

be excavated from site is 6 600 tons and 630 tons respectively in a wet form. These represent the weight of masses for transportation to the incinerator. Only the dry weight of the masses will be incinerated. In this study, it was assumed that the dry weight of bark and peat will be 1 898 tons and 273 tons respectively based on Kemakta (2012), see Appendix A for the calculations. In this respect, incineration of 1 898 tons of dry bark and 273 tons of dry peat from Långö will result in 114 tons and 12 tons of ash respectively, making a total amount of 126 tons ash. This total amount of ash will be washed and followed by metal recycling. The amounts of wet clay and glacial till that will be excavated are 1 660 and 580 tons respectively but their dry weight will only be considered for a liquid-solid ratio of 3 during soil washing[6].

3.4.1 Remediation Alternative 1

The logistics for the excavated and treated contaminated material in *Alternative 1* is presented in Figure 3.2. *Alternative 1* assumes transportation of bark and peat from the site Långö to the nearest incineration facility in Uddevalla by boat and truck. The bark and peat are mixed with other waste and incinerated. The ash after incineration is further transported by boat to NOAH and landfilled at Langøya, Norway. The contaminated soil (clay and glacial till) is excavated and transported to NOAH directly for landfilling without any pre-treatment.

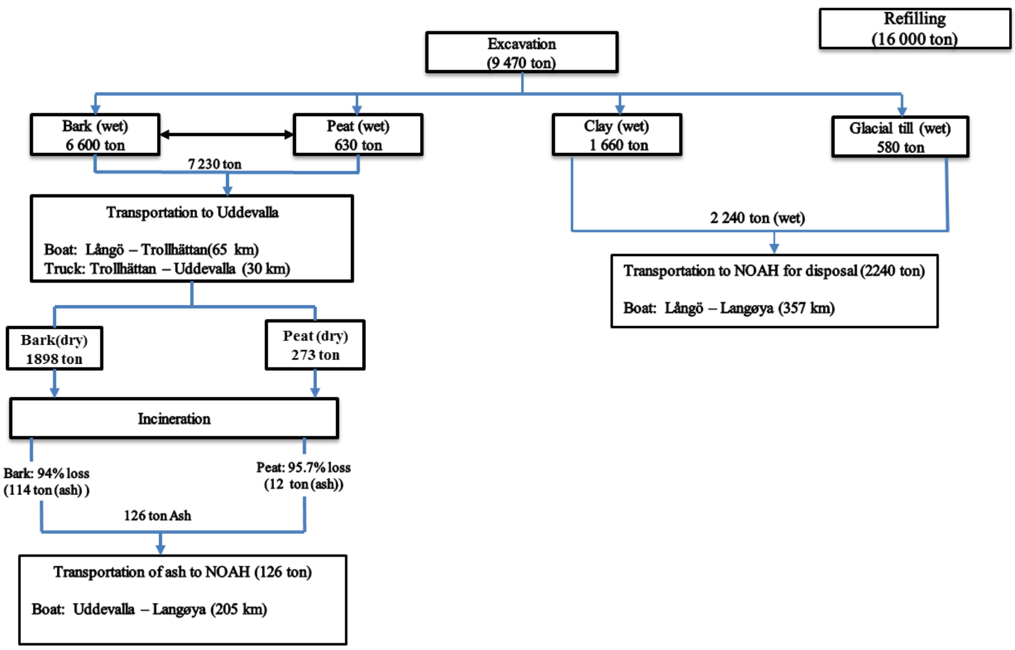

Figure 3.2. Overview of the remediation process in Alternative 1. Figure by Yevheniya Volchko. Transportation distances and amounts are refined by Abibat Adedigba.

[6] Karin Karlfeldt Fedje, Supervision meeting, 2015-05-27

3.4.2 Remediation Alternative 2

The logistics for the excavated and treated contamination material in *Alternative 2* is presented in Figure 3.3. In this alternative, the excavated bark and peat will be transported to Svenljunga for incineration and the ash from the combustion of bark and peat is transported to Göteborg for ash washing. A copper rich metal sludge is produced by the ash washing process and is then sold and transported to Boliden AB for copper recovery. Boliden AB is a mining and smelting company in Rönnskär in the Skellefteå municipality, Sweden. The hazardous solid residue after ash washing is transported to the NOAH landfill, Langøya, Norway. The excavated contaminated soil (clay and glacial till) is transported directly to NOAH with no pre-treatment before landfilling.

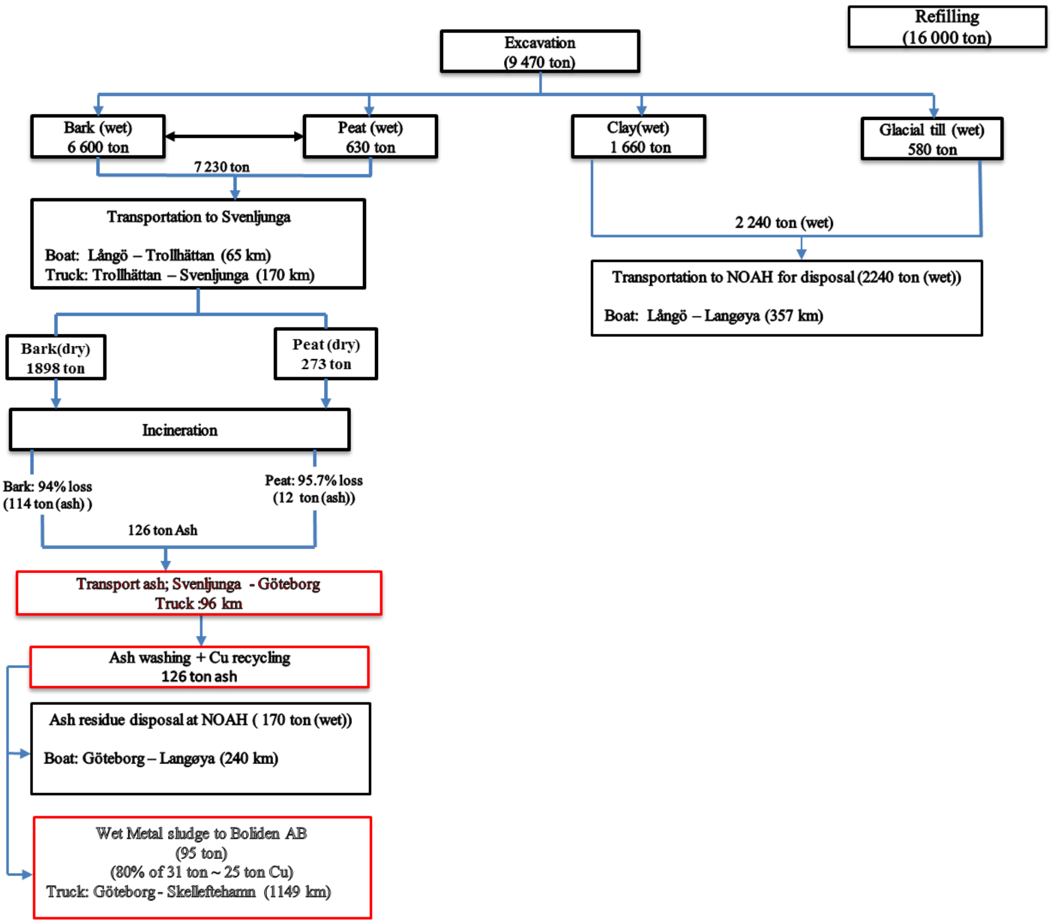

Figure 3.3. Overview of the remediation process in Alternative 2. Figure by Yevheniya Volchko. Transportation distances and amounts are refined by Abibat Adedigba

3.4.3 Remediation Alternative 3

The logistics for the excavated and treated contamination material in *Alternative 3* is presented in Figure 3.4. In *Alternative 3*, bark and peat will be treated the same way as in *Alternative 2*. The ash washing is done in Göteborg and the metal product (metal sludge) resulting from the process is sold to Boliden AB and transported to Skelleftehamn. In this alternative the residue after ash washing is stabilised and landfilled locally in Partille The excavated contaminated soil (clay and glacial till) is transported to Göteborg and landfilled locally without pre-treatment.

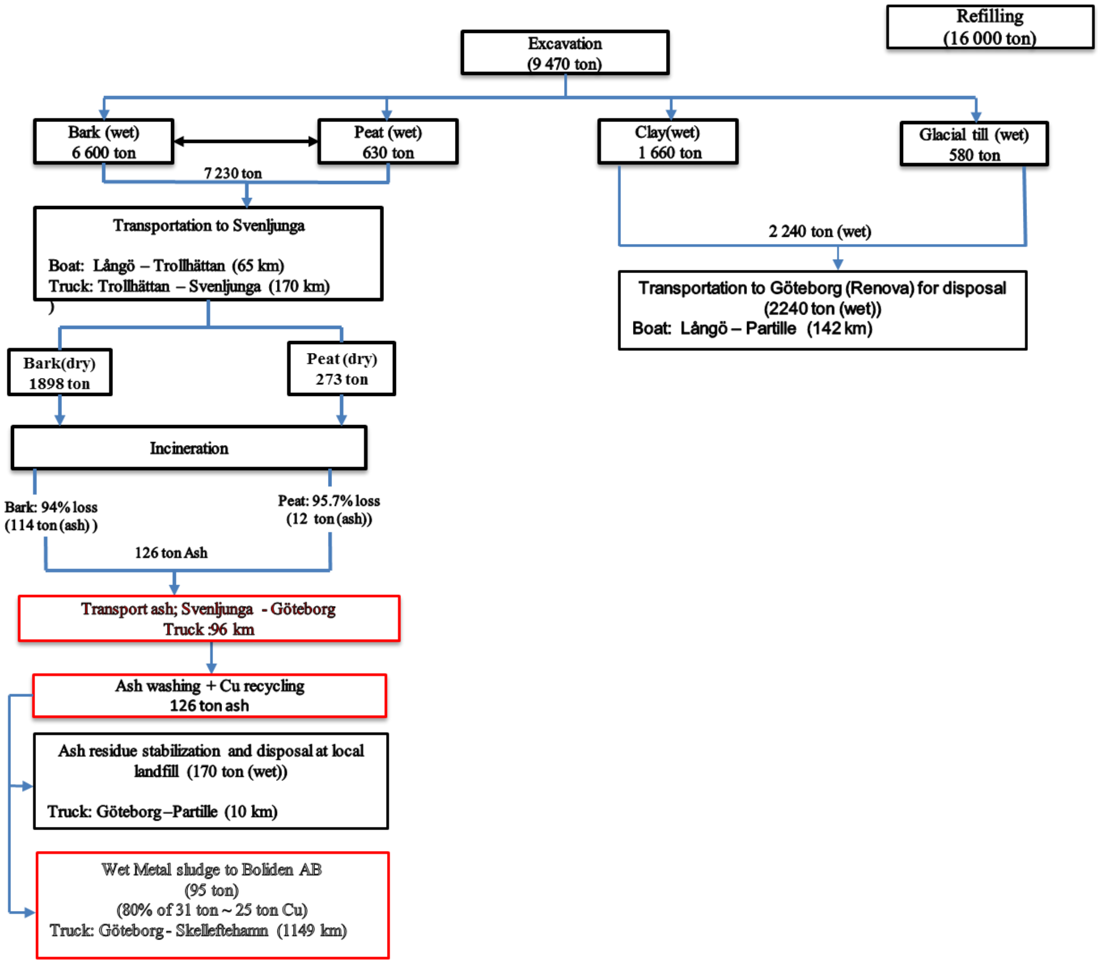

Figure 3.4. Overview of the remediation process in Alternative 3. Figure by Yevheniya Volchko. Transportation distances and amounts are refined by Abibat Adedigba

3.4.4 Remediation Alternative 4

The logistics for the excavated and treated contamination material in *Alternative 4* is presented in Figure 3.5. *Alternative 4* is the same as *Alternative 2*, but ash washing is not considered in the process. Ash from incineration is sold and transported directly to Boliden AB in Skelleftehamn for metal recovery. The excavated contaminated soil (clay and glacial till) is transported to NOAH for disposal.

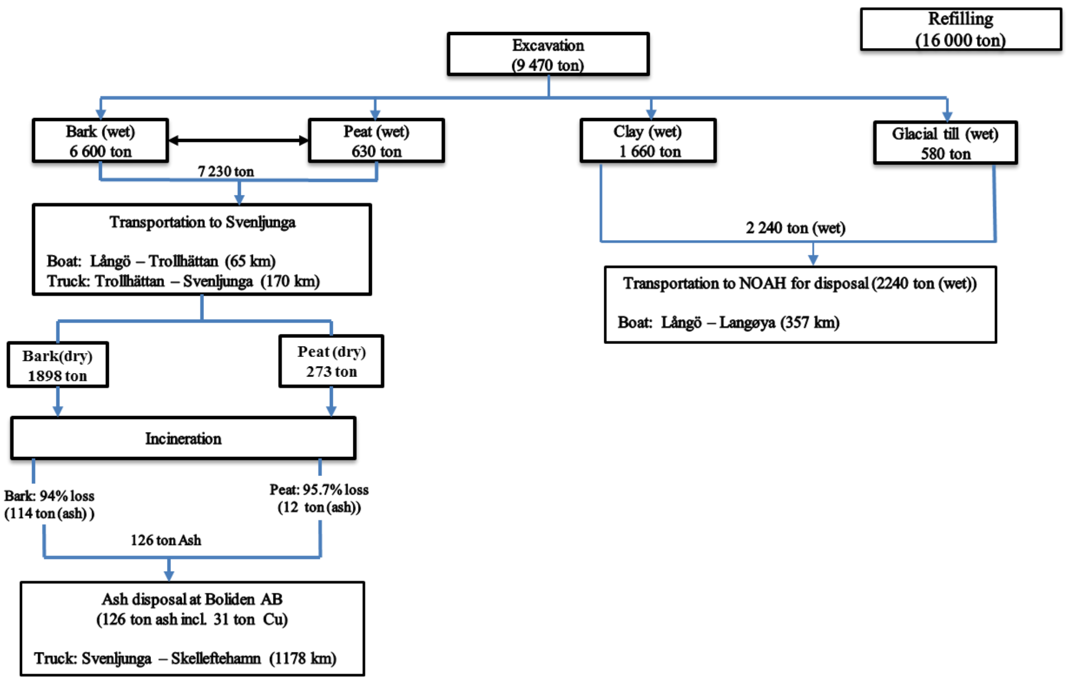

Figure 3.5. Overview of remediation process in Alternative 4. Figure by Yevheniya Volchko. Transportation distances and amounts are refined by Abibat Adedigba

3.4.5 Remediation Alternative 5

The logistics for the excavated and treated contamination material in *Alternative 5* is presented in Figure 3.6. Bark and peat are excavated and transported to Svenljunga for incineration, Ash from the incineration is transported to Göteborg for washing and metal sludge from the precipitation of the leachate is sold and transported to Boliden AB. The residue from the ash washing is stabilized and transported for deposal at a local landfill in Partille. This alternative includes also sieving and soil washing. The excavated mineral soil from Långö is transported to Goteborg. Only the glacial till is sieved to obtain a finest smaller particle size before washing. Clay is wash directly. Moreover, sieving serves as a pre-treatment prior to soil washing and it enables optimization of leachate from the process. The leachate then precipitates to form metal sludge for metal recovery. The residue from soil washing is stabilized and landfilled locally in Partille while the metal sludge obtained after soil washing is sold and transported to Boliden AB.

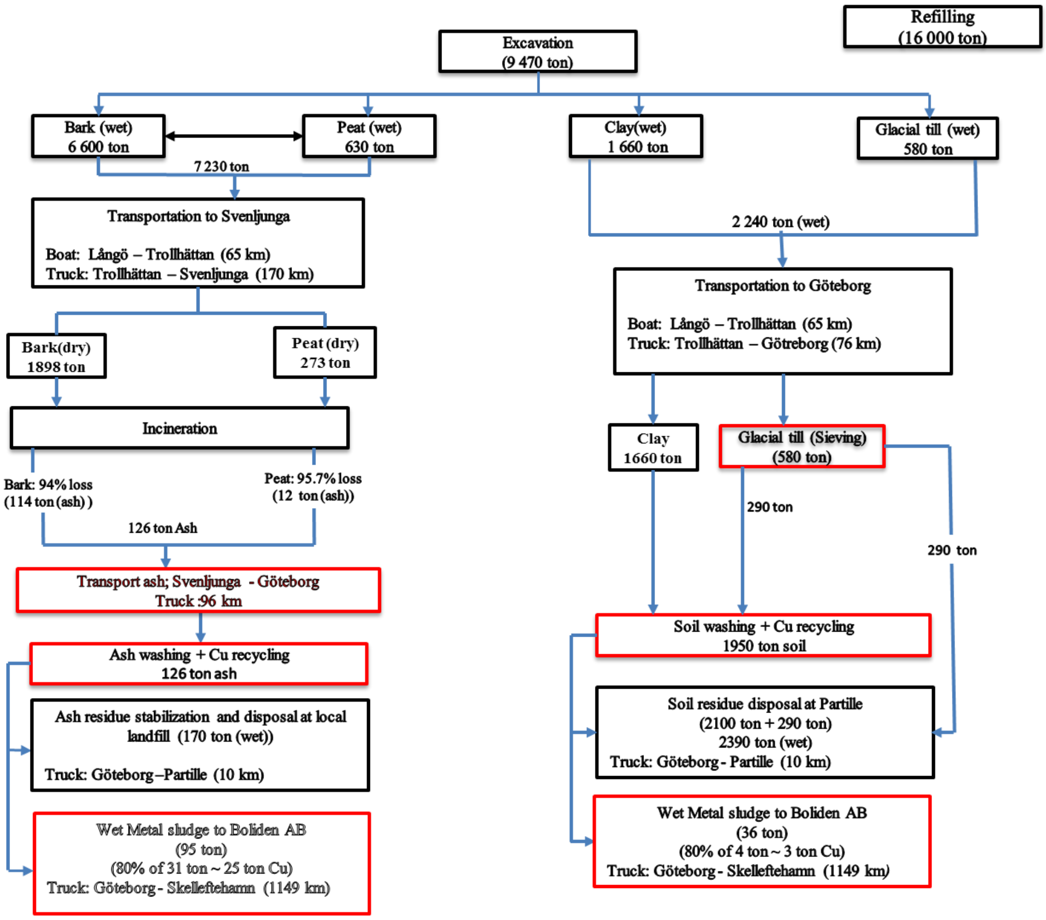

Figure 3.6. Overview of the remediation process in Alternative 5. Figure by Yevheniya Volchko. Transportation distances and amounts are refined by Abibat Adedigba

For summary of remediation alternatives see Table 3.1.

Table 3.1. Summary of all the 5 alternative remediation activities.

Alternative	Bark and peat incinerated with other waste (Uddevalla)	Bark and peat incinerated separately (Svenljunga)	Soil directly landfilled (Place)	Cu recycling from ash	Cu recycling from soil
1	×		× (Langøya)		
2		×	× (Langøya)	×	
3		×	× (Partille)	×	
4		×	× (Langøya)		
5		×		×	×

4. Methods

4.1 Overview of Leaching Procedure

In this study assumptions related to the copper leaching process were extrapolated from the previous research work by Karlfeldt Fedje et al. (2013) and WR-58 (2013). The whole ash leaching process involves two washing steps, acid washing and water washing as indicated in the flow-chart presented in Figure 4.1. It is assumed that incineration of 1 898 tons of dry bark and 273 tons of dry peat (which is done separately from other wastes at Svenljunga incinerator) will result in 126 tons of ash with reference to the loss on ignition of bark and peat according to Bränslehandboken (2012) and as explained in Section 3.4.

Ash is highly alkaline in nature and leaching of metals from ash requires strong acidic solutions. Process water from flue gas is highly acidic and contains high concentration of chlorides and suitable chemically and economically to leach about 80-90% of metals out of ash with the liquid-solid ratio of 3 (Karlfeldt Fedje et al., 2013).

4.1.1 Copper in bark and peat

A total amount of 378 m^3 of process water equivalent to 378 tons (assuming process water density equal water density) is required for treatment of 126 tons of the ash produced after incineration of the bark and peat. The mixture of ash and process water is filtered to obtain the leachate equal to 334 tons and the ash residue equal to 170 tons. Thereafter, the leachate and residues are separately treated. The ash leachate is acidic and it requires an alkaline chemical substance like sodium hydroxide (NaOH) to precipitate the metal sludge. The amount of NaOH which is required for 334 tons leachate is calculated to be about 4 tons (for details see Appendix B). The precipitated metal sludge is washed with ordinary water to lower the chlorides concentration obtained from the process water. According to Karlfeldt Fedje (2015)[7], the amount of metal sludge that will be precipitated from the leachate can be calculated separately as follow (Figure 4.1). 126 tons of ash after incineration of dry bark and peat contain about 31 ton of copper (Kemakta, 2012). Assuming that 80% of copper is recoverable, the amount of obtained copper will be equal to 25 tons. In the recent lab experiment on metals precipitation from ash and soil leachate during the soil washing process, it was observed that 40% of the total metal sludge (in dry weight) formed after ash leachate precipitation consists of copper (Andersson & Lundström, 2015). Thus, it is assumed that 25 tons of copper are recovered after washing of 126 tons of the ash. Consequently, the total metal sludge amount will be 63 tons in dry weight. As it is assumed that the metal sludge will be transported in wet form after leaching and precipitation, the total amount of 63 tons of dried sludge is multiplied by1.5 to account for present water (the sludge will contain approximately 50% of water). Thus, 95 tons of the wet metal sludge will be generated in result of leaching and precipitation. It is also assumed that the amount of wet copper sludge in form of $Cu(OH)_2$ equals to approximately 38 tons. The

[7] Supervision meeting, Chalmers University, 2015-04-30

wet metal sludge also contains other elements such as aluminium and iron in a quite large amounts but recycling of these metals are not investigated in the study. The wet metal sludge is transported to Boliden AB mining and smelting company in Skellefterhamn for copper recovery. The ash residue is washed with water to stabilize the ash before landfilling. It is assumed that a total of 170 tons wet clean ash residue is transported to the landfill site but only 113 tons of the dry clean ash residue will be landfilled.

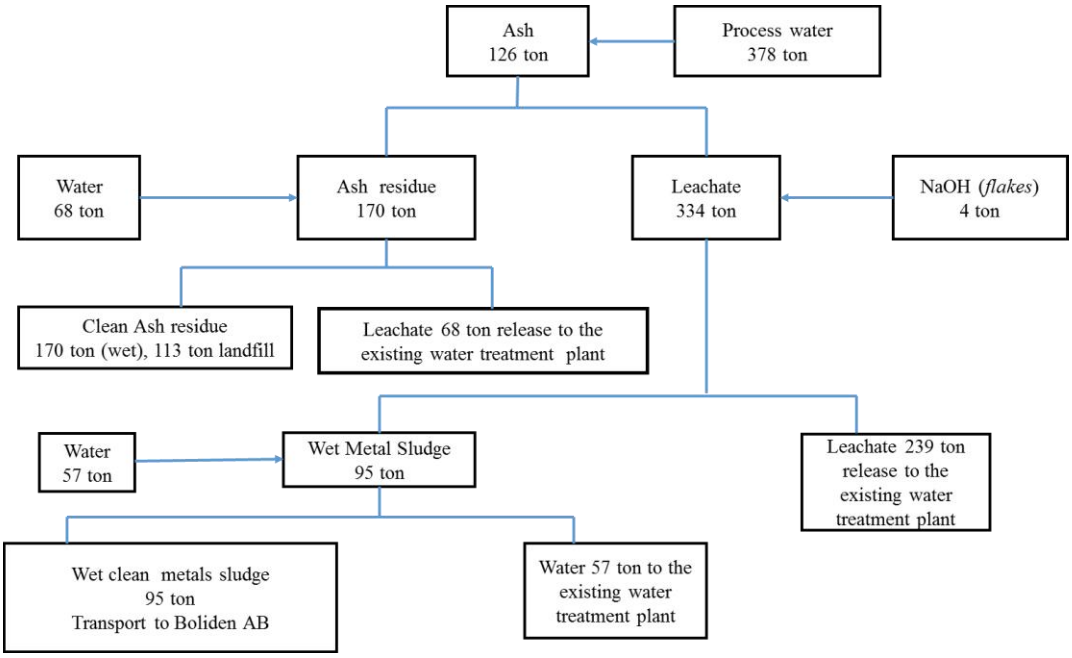

Figure 4.1. Flow-chart of Ash leaching procedure.

A liquid/solid ratio of 3 is used in the acid leaching process, 126 tons of ash requires 378 $m^3$of process water. Density of process water is assumed to be the same as for water (equals to 1). The required amount of process water is 378 tons (equivalent to 378 m^3 of water). In the washing process (in particular, water leaching), a liquid/solid ratio of 0.6 is enough (i) to reduce concentration of chlorides in the ash residue and metal sludge, (ii) to stabilize the ash residue for landfill and (iii) to increase the metal sludge value (price) (Karlfeldt Fedje, 2015)[8].

4.1.2 Copper in the soil

The soil at the Långö site consists of clay and glacial till and it contains about 4 tons of copper (Kemakta, 2012). Soil leaching procedure is the same as in the ash leaching procedure (see Section 4.3.1 and Figure 4.2). However, in this procedure, glacial till is sieved instead of incinerating to consolidate smaller size soil particles and obtain the fine soil for optimization of a soil washing process. After sieving, the finest particle size of glacial till equals 290 tons (i.e. a half of its initial amount; assumption is based on Kemakta, 2012). The smaller size particles of glacial till (290 tons) will be added to clay (1 660 tons) making a total of 1 950 tons the fine soil, which is further washed with

[8] Karin Karlfeldt Fedje, Supervision meeting, 2015-02-25

process water. The dry soil amount was calculated to be 1 555 tons, assuming the liquid-solid ratio of 3. Based on the dry soil weight, it is estimated that 4 665 tons of acidic process water (assuming process water density equal water density) is required for leaching 80-90% of copper from 1 950 tons of fine soil. The mixture of soil and process water is filtered to obtain the leachate of 4 121 ton and soil residue of 2100 tons which are then treated separately. The amount of NaOH require for 4 121 ton leachate is calculated to be approximately 52 tons (see Appendix A). According to Andresson and Lundström (2015), in the soil leachate after precipitation, only 13% of dry metal sludge is copper. Based on these results, it is assumed that 24 tons of the dry metal sludge will be generated after precipitation of 4 121 ton of the soil leachate when 52 tons of NaOH is being added. The amount of wet metal sludge equals to 24 tons multiplied by 1.5 (assuming 50% of water in the sludge) which gives 36 tons of the wet metal sludge and approximately 5 tons of $Cu(OH)_2$. These 36 tons of wet metal sludge will be transported to Boliden AB for copper recycling. The amount of clean soil residue that will be transported to the landfill site is estimated to 2 100 tons while 1 400 tons will actually be landfilled after dewatering (see the low-chart in Figure 4.2).

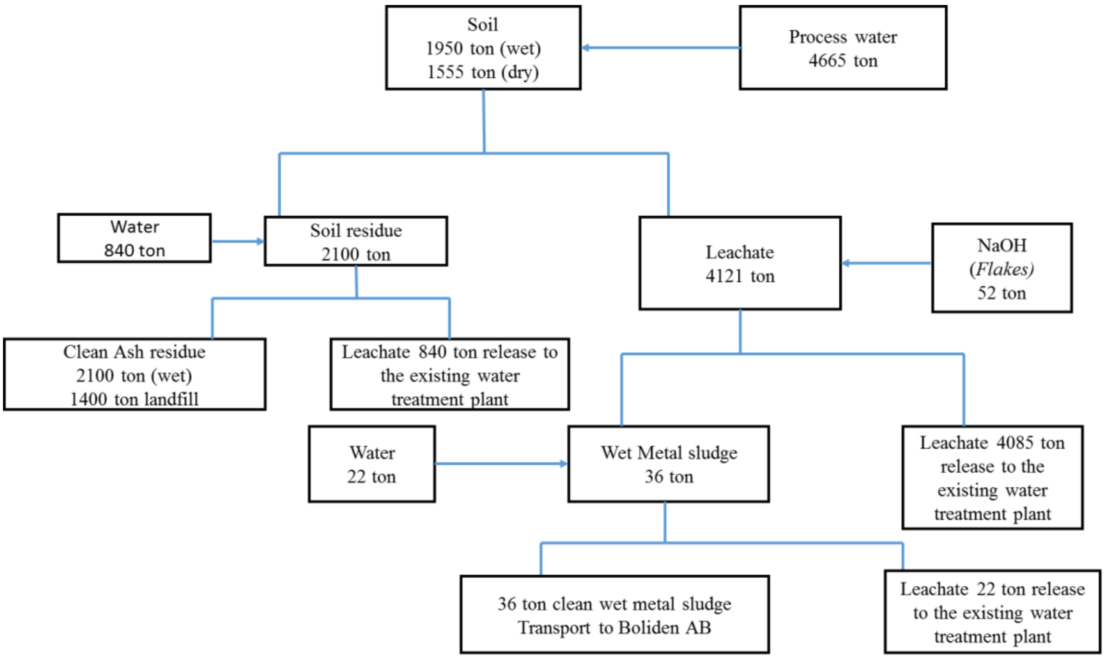

Figure 4.2. Flow-chart of soil leaching procedure.

4.2 Economic valuation

Cost-benefit analysis (CBA) is used to evaluate social profitability of metal recycling in conjunction with remediation at the Långö site. This method expresses positive effects (benefits) and negative effects (costs) of remediation in monetary units taking into consideration time aspects. In this study, the uncertainty surrounding these monetary units are taken into explicit account with Monte Carlo simulation as suggested in Brinkhoff (2014), Söderqvist et al. (2015), Rosén et al., (2013), see also Section 2.4. A discount rate is used to convert future benefits and costs into a present value. However, not all costs and benefits can be monetized and it is therefore important to perform qualitative assessment of these items (Rosén et al., 2013).

In this thesis, all estimations of costs and benefits were based on the previous work by Yevheniya Volchko[9], reports in Elander (2014) and Kemakta (2012) and the expert judgment about the site. Moreover, benefit transfer is used to estimate WTP for improved groundwater quality in the contaminated area. Copper and lead are the major contaminants at the study site according to Kemakta (2012), therefore only these two contaminants are taken into consideration in the CBA.

4.2.1 Identification of costs and benefits

The costs and benefits identified to be relevant for remediation at the Långö site are ranked according to their importance (Table 4.1).

All costs evaluated and estimated for Långö site remediation were described as followed. *Remediation costs* (C1); based on the available data and time, the cost associated with *remediation action* (C1d) and *monitoring* (C1e) was only estimated for and the two costs are very important. The cost of *design of remedial action* (C1a) is included in (C2) and as ranked as not important. *Capital costs (*C1c) is regarded of no importance for this case, because the capital will be locked only one year, see Appendix C. *Project management* (C1b), and *project risks* (C1f) are important but not monetized in thesis due to time constraints. *Impaired health due to remedial action* (C2) which includes both *increased health risks due to measure on the site* (C2a) and *increased health risks due to transportation* (C2b) are equally important in the analysis. The most important sub-item costs in the *decreased provision of ecosystem services due to remedial action* (C3) category are *decreased provision of ecosystem services on site* (C3a) and *decreased provision of ecosystem services in the surroundings* (C3b). They are ranked as very important due to the amount of greenhouse gas emissions associated with transportation of the material from and to the site and the remediation equipment used on site. The *decreased provision of ecosystem services at disposal sites* (C3c) considered of no importance, because landfills considered in this study are assumed to be located at the well-planed places with low ecological value. *Other negative externalities than C2 and C3* (C4) such as costs associated with noise and air pollutants due to transportation is very important.

[9] The following spreadsheet models with preliminary calculations by Yevheniya Volchko for the five remediation alternatives have served as input for this study:

- The SCORE-model with preliminary calculations of the costs and benefits,
- The TrExTool model with preliminary calculations of greenhouse gas emissions due to transportation,
- The spreadsheet model with preliminary calculations of the benefits associated with decreased health risks due to contamination,
- The spreadsheet model with preliminary calculations of the costs due to increased health risks on-site,
- The spreadsheet model with preliminary calculations of the costs associated with increased health risks due to transportation,
- The spreadsheet model with preliminary calculations of WTP for improved groundwater quality.

Table 4.1 Identification of costs relevant for the Långö site, where"X" implies high importance, "(X)" implies some importance and "0" implies no importance[10].

Costs	**Importance**
C1. Remediation costs	
C1a. Design of remediation	0
C1b. Project management	(X)
C1c. Capital costs	0
C1d. Remedial action	X
C1e. Monitoring	X
C1f. Project risks	(X)
C2. Impaired health due to remedial action	
C2a. Increased health risks on site	X
C2b. Increased health risks from transport activities	X
C2c. Increased health risks at disposal site	0
C2d. Other types of impaired health e.g. increased anxiety	0
C3. Decreased provision of ecosystem services due to remedial action	
C3a. Decreased provision of ecosystem services on site	X
C3b. Decreased provision of ecosystem services in the surroundings	X
C3c. Decreased provision of ecosystem services at the disposal sites	0
C4. Other negative externalities than C2 and C3 e.g. noise and air pollutants	X

The relative importance of benefits resulting from remediation at the Långö site is presented in Table 4.2. First, it is important to stress that Långö is located in suburban area of Västra Götaland County with undeveloped infrastructure. Due to this factor, *increase in land value* (B1) after remediation was not considered as important. The site is assumed to serve for the public recreation purposes after remediation, but it is not likely that more individuals than those using five present summer households will visit the site. Lack of data and time had made it impossible to evaluate the possibility of remediation action on the site to *increased recreational opportunities on site and its surroundings* (B3a and B3b). The main benefit of a remediation at Långö is probably to *improve health* (B2); *reduced chronic (non-acute) health risks* (B2b) of the site for

[10] The initial table by Yevheniya Volchko was revised with regard to importance of the costs associated with project management and other types of impaired health due to elimination of the need for quay construction.

recreational purposes was considered to be very important in term of social profitability perspective. This benefit is assumed to be present in 200 years.

Another benefits considered to be estimable is the *increased provision of ecosystem services* (B3). B3a and B3b associated with increased recreational opportunities on site and in the surroundings are somewhat important, because there are not that many visitors due to location of the site. However, the re-established vegetation creates recreational opportunities on the site and in the surrounding attracting more visitors.An improvement in the groundwater quality (fresh water) in the Långö area is somewhat an important benefit and estimated for via *increased provision of other ecosystem services* (B3c). The site is highly contaminated with copper which is a very valuable natural resource. Recycling the copper metal instead of landfill was considered very import and categorised as *other benefits* (B5) as separate from (B4) *other positive externalities than B2 and B3.* All possible benefits and their importance are presented in Table 4.2.

Table 4.2. *Identification of benefits resulting from remediation at the Långö site, where "X" implies high importance, "(X)" implies some importance and "0" implies no importance*[11].

Benefits	Importance
B1. Increase in land value	0
B2. Improve health	
B2a. Reduce acute health risk	0
B2b. Reduced chronic (non-acute) health risks	X
B2c. Other types of reduced health risks	0
B3. Increased provision of ecosystem services	
B3a. Increased recreational opportunities on site	(X)
B3b. Increased recreational opportunities in the surroundings	(X)
B3c. Increased provision of other ecosystem services	(X)
B4. Other positive externalities than B2 and B3	0
B5. Other benefits	X

4.2.2 Time horizon

An overview of the time plan reflecting occurrence of costs and benefits is presented in Appendix C. The remediation project at Långö is assumed to take one year based on Elander (2014). As already mentioned above, the only possible way to the Långö site

[11] No changes were made in the initial table by Yevheniya Volchko, where the B5 benefit item was identified as very important and included into a CBA model for the Långö site.

is by boat, which implies special arrangements for on-off loading of the excavated masses. According to Elander (2014), construction of quay at site for on-off loading of the excavated masses should be eliminated which is in contradiction to the suggestion in Kemakta (2012). Elimination of quay construction rules out the need for seeking a permit from authorities which usually takes 2-3 years to process (Kemakta, 2012). A time horizon of 200 years[12] is chosen for evaluation of the reduced long-term health risks to the public and increased provision of other ecosystem services such as quality fresh water in the area. Increased health risks due to the remedial action and transportations are of importance during year one.

4.2.3 Uncertainty and sensitivity analyses

Uncertainty and sensitivity analyses should be included in the CBA as stressed in Rosén et al. (2008, 2013), Söderqvist et al. (2015). In this thesis, Monte Carlo simulations (MCS) are realised with help of MS Excel add-in Oracle™ Crystal Ball, in order to perform uncertainty and sensitivity analyses. Triangular statistical distribution is chosen to represent uncertainties in the cost and benefit items. The minimum, likeliest and maximal values are assigned to each variable in each alternative to calculate uncertainties in the resulting Net Present Value (NPV), see Appendix J. Two types of sensitivity analysis were performed. Firstly, the sensitivity of each variable in each remediation alternative was examined to see which of the variable has the highest effect on the resulting NPV. Secondly, discount rates of 3.5%, 1.4% and 0% were used to examine how the NPV varies with different discount rates (Rosén et al., 2008).

4.3 Estimating willingness-to-pay for improved groundwater quality at Långö[13]

Benefits associated with increased provision of such ecosystem service as fresh water at the Långö site is estimated through WTP for improved water quality in the wells. Improvement of groundwater quality from remediation is assumed to be an important benefit in this study. WTP for an improvement of environmental goods and service is usually carried by valuation methods such as contingent valuation methods (CVM), choice experiment (CE), hedonic pricing and travel cost (TC) as mentioned in Chapter 2. All of these valuation methods are usually costly and time consuming.

Benefit transfer is considered to be the most cost-effective and time-efficient method with regard to the Långö site where a few households are affected. According to Kriström & Bonta Bergman (2014), the easiest way is to begin with potential valuation studies in the existing databases, while assessing their reliability and suitability for

[12] Yevheniya Volchko, supervision meeting, Chalmers University. 2015-03-10

[13] The thorough literature review and complementary searches in databases were performed in this study. The preliminary calculations of WTP for improved groundwater at the Långö site performed by Yevheniya Volchko were not changed.

value transferring. According to Kriström & Bonta Bergman (2014), suitability of the studies for value transferring is evaluated using the following criteria:

- point value estimates are used instead function transfer,
- transfer error is at least 25-40 percent,
- used when there are large direct use values in additional relation to the indirect values,
- used rather for non-market goods and services than for market products and services
- study areas are similar with policy area in term of income levels, cultural conditions,
- the valuation studies that are older than ten years are used with extreme caution or avoided.

The Swedish Value Base was, thus, first checked to see if there is any case similar to Långö. A study carried by Silvander (1991) on WTP for groundwater of good quality in Sweden is a suitable valuation study but was omitted because it is older than ten years. Moreover, a thorough literature review of valuation studies examining WTP for groundwater in Sweden was carried out, but there were no any relevant studies found. The next step as recommended by Kriström & Bonta Bergman (2014) is to look after valuation studies done in other Nordic countries. The compilation of valuation studies carried out in Nordic countries can be found in Nordic Environmental Valuation Database (NEVD) which is part of the largest global database of valuation studies Environmental Value Reference Inventory (EVRI).

In NEVD several valuation studies on WTP for improved water quality were found and the most relevant study to the Långö case was the report by Hasler et al. (2005). The estimated WTP for purified water is 529DKK/household/year (in 2004 DKK). Moreover, to test the validity of a value transfer, it is recommended to estimate the value from two (or more) valuation studies taking into consideration *"transfer error"* (TE) (Kriström & Bonta Bergman, 2014). In this respect, the valuation study by Rinaudo and Aulong (2013) was considered. Rinaudo and Aulong (2013) estimated WTP for groundwater protection in Rhine valley aquifer, France. The French study was found relevant because there are similarities in attitudes or concerns on improvement of groundwater among citizens of Sweden and France (EORG, 2002). The average WTP for restoring drinking-water quality standards in the aquifer after remediation was estimated to 42 Euro/household/years (in 2006 Euro). The values from the above two studies were corrected for income and converted to the present Swedish crown value that equals to 661 SEK and 547 SEK /household/year respectively. The WTP to improve water quality in the wells at the Långö site was estimated to be 604 SEK/household/year (in 2015 SEK), which is equivalent to 3 020 SEK for all the five households per year. See Appendix D for detailed conversions to Swedish crowns and calculations.

5. Results

5.1 Quantification of costs and benefits

The monetary value of all the identified costs and benefits are estimated for calculation of the NPV. All the costs of remediation are not discounted because remediation activities assume to take place within one year according to Elander (2014). This report eliminates the need of dredging of the contaminated sediment for construction of quay for on- and off-loading of the excavated masses. However, the benefits resulting from remediation action were discounted over a horizon of 200 years.

The cost associated with remedial action (C1d) considers remediation and restoration works. The former includes costs for excavation, transportation of contaminated soil and disposal at landfills. The latter includes costs for refilling material, water treatment and re-establishment of vegetation. All the five remediation alternatives assume similar activities except for transportation to different landfill locations. In addition, *Alternatives 2, 3 and 5* assume costs for ash and soil washing. Cost estimations are based on data provided by Kemakta AB (Kemakta, 2012), Elander Miljöteknik AB (Elander, 2014) and the tender made by SoilTech in 2009 (Landström & Östlund, 2011). The cost for monitoring (C1e) is based on Kemakta AB (Kemakta, 2012).

Impaired health due to remedial action and increased health risks due to the remedial measure on site are calculated with help of the Spatial Analysis and Decision Assistance (SADA) software. Increased health risks resulting from transportation of (C2b), which implies traffic accidents that might happen during the transportation of the excavation masses that can result in severe injury to human and potential hazard to some area. Calculations of accident probabilities are based on data from the Swedish Road Authority (1998). The costs associated with severe injuries from a traffic accident are based on *Value of Statistical Life* (VSL) provided in SIKA (2009). See Appendices E & F for calculations.

Costs for decreased provision of ecosystem services due to remedial action on-site (C3a) are based on CO_2-emissions equivalents extrapolated from data provided in Brycke et al. (2013). Costs associated with decreased provision of ecosystem services in the surroundings (C3b) are based on emissions of greenhouse gases calculated with TrExTool (TrExTool, 2009) and their costs provided in SIKA (2009). See Appendix G for calculations.

Other negative externalities than C2 and C3 in form of noise, NO_x and SO_2 (C4); are calculated using TrExTool and costs for of emissions (SIKA, 2009). See Appendix H for calculations.

The summary of all the costs associated with remediation is presented in Table 5.1.

Table 5.1 Quantified and monetized costs associated with remediation at the Långö site. The costs are discounted at 3.5% (see Appendix C for details).

Costs	Alt.1, MSEK	Alt.2, MSEK	Alt.3 MSEK	Alt.4 MSEK	Alt.5 MSEK
C1. Remediation costs					
C1a. Design of remediation	-	-	-	--	-
C1b. Project management	-	-	-	-	-
C1c. Capital costs	-	-	-	-	-
C1d. Remedial action	13.0284	15.7620	16.3128	15.5094	17.7907
C1e. Monitoring	0.4515	0.4515	0.4515	0.4515	0.4515
C1f. Project risks	-	-	-	-	-
C2. Impaired health due to remedial action					
C2a. Increased health risks on site	1.1031	1.1031	1.1031	1.1031	1.1031
C2b. Increased health risks from transport activities	0.0322	1.1587	1.1753	1.0998	2.6188
C2c. Increased health risks at disposal site	-	-	-	-	-
C2d. Other types of impaired health e.g. increased anxiety	-	-	-	-	-
C3. Decreased provision of ecosystem services due to remedial action					
C3a. Decreased provision of ecosystem services on site	0.0152	0.0152	0.0152	0.0152	0.0152
C3b. Decreased provision of ecosystem services in the surroundings	0.1491	0.3050	0.2688	0.3060	0.2902
C3c. Decreased provision of ecosystem services at the disposal sites	-	-	-	-	-
C4. Other negative externalities than C2 and C3, e.g. noise and air pollutants (NO_x and SO_2)	0.0794	0.1209	0.0937	0.1199	0.0912
Total discounted cost	**15**	**19**	**19**	**19**	**22**

Reduced chronic (non-acute) health risks posed by copper and lead, B2b, are considered as most important factor in remediation. These two chemical substances are carcinogenic and toxic to human health[14]. The benefit is calculated as the difference between the non-acute health risk for the reference alternative and the generic target risk for cancer. Risk calculations in SADA (2007) application are performed for Cu-64 and Pb-200 representing copper and lead assumed to present at the Långö site respectively. See Appendix I for calculations.

Increased recreational opportunities on site within the site, B3a, and increased recreational opportunities in the surroundings, B3b, are very important benefit items but it is difficult to monetize them due to associated costs and time constraints of this Master's thesis work. However, increased provision of other ecosystem services, B3c, is monetised using the benefit transfer method. See Section 4.3 and Appendix D for details.

Although other benefits (B5), e.g. income from copper recovery, are not considered in the CBA by Rosén et al. (2008, 2013), Söderqvist et al. (2015), they are included in this study, because of their high importance in the Långö case. The worth of recoverable

[14] Consultation meeting with Jenny Norrman, Chalmers University of Technology., 2015-07-03.

copper from Långö site was estimated based on assumption that Cu price per ton is 0.05MSEK[15]. Alternatives 2 and 3 assume 25 tons of Cu recoverable while alternative 5 assumes 30 tons of Cu recoverable. The worth of Cu for *Alternatives 2*, *3* and *5* are 1.25, 1.25 and 1.5MSEK respectively.

The summary of all the discounted benefits associated with remediation is presented in Table 5.2.

Table 5.2 Quantified and monetized benefits associated with the remediation and copper recycling at the Långö site. The benefits are discounted at 3.5% and a time horizon of 200 years (see Appendix C for details).

Discounted Benefits	Alt.1 MSEK	Alt.2, MSEK	Alt.3, MSEK	Alt.4, MSEK	Alt.5, MSEK
B1. Increased land value	0	0	0	0	0
B2. Improve health					
B2a. Reduce acute health risk	**-**	**-**	**-**	**-**	**-**
B2b. Reduced chronic (non-acute) health risks*	0.1393	0.1393	0.1393	0.1393	0.1393
B2c. Other types of reduced health risks					
B3. Increased provision of ecosystem services					
B3a. Increased recreational opportunities on site	-	-	-	-	-
B3b. Increased recreational opportunities in the surroundings	-	-	-	-	-
B3c. Increased provision of other ecosystem services	0.0832	0.0832	0.0832	0.0832	0.0832
B4. Other positive externalities than B2 and B3	-	-	-	-	-
B5. Other benefits (metal recycling)	0	1.1669	1.1669	0	1.4003
Total discounted benefit	**0.2**	**1.4**	**1.4**	**0.2**	**1.6**

5.2 Uncertainty and Sensitivity analyses

The NPV results for all the five alternatives using a recommended discount rate of 3.5% shows that all the alternatives have a negative NPV. Alternative 1 has the lowest negative NPV of -14.64 MSEK and at 90% credibility interval the NPV is [-15.53, -13.75]. The statistical distribution of NPV for *Alternative 1* is shown in Figure 5.1.

[15] Elander Miljöteknik AB (2014)

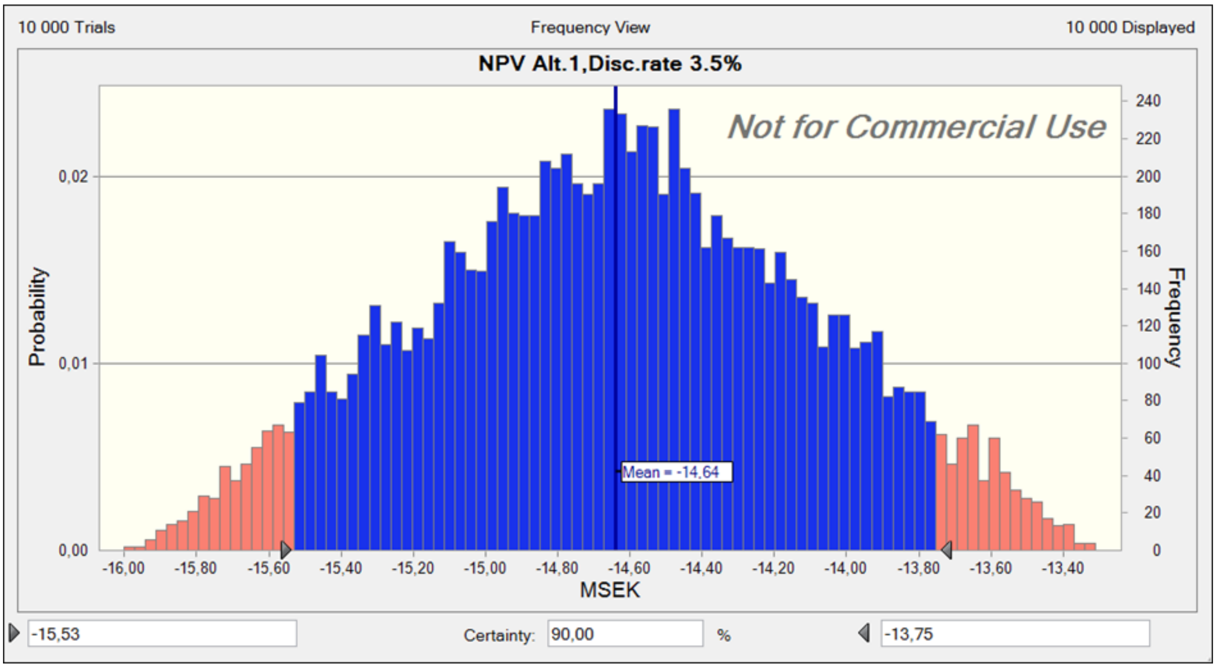

Figure 5.1. Simulation result showing the statistical distribution for NPV in Alternative 1, i.e. excavation and direct landfilling of the soil at NOAH, excavation and incineration of bark and peat in Uddevalla followed by disposal of the ash at NOAH. See Table 3.1 for overview of alternatives.

NPVs for *Alternatives 2*, *3*, *4* and *5* were -17.64 MSEK, -18.03 MSEK, -18.38 MSEK, -20.74 MSEK respectively. When costs and benefits discounted at 3.5%, *Alternative 1* is the most cost effective one. However, this alternative is the least recommended choice for site remediation, because the soil contaminated with metals is landfilled instead of metal recycling in combination with remediation. See Figures 5.2-6 for the distributions of NPV for *Alternatives 2-5* with the discount rate of 3.5% and the overlay forecast chart of all the alternatives.

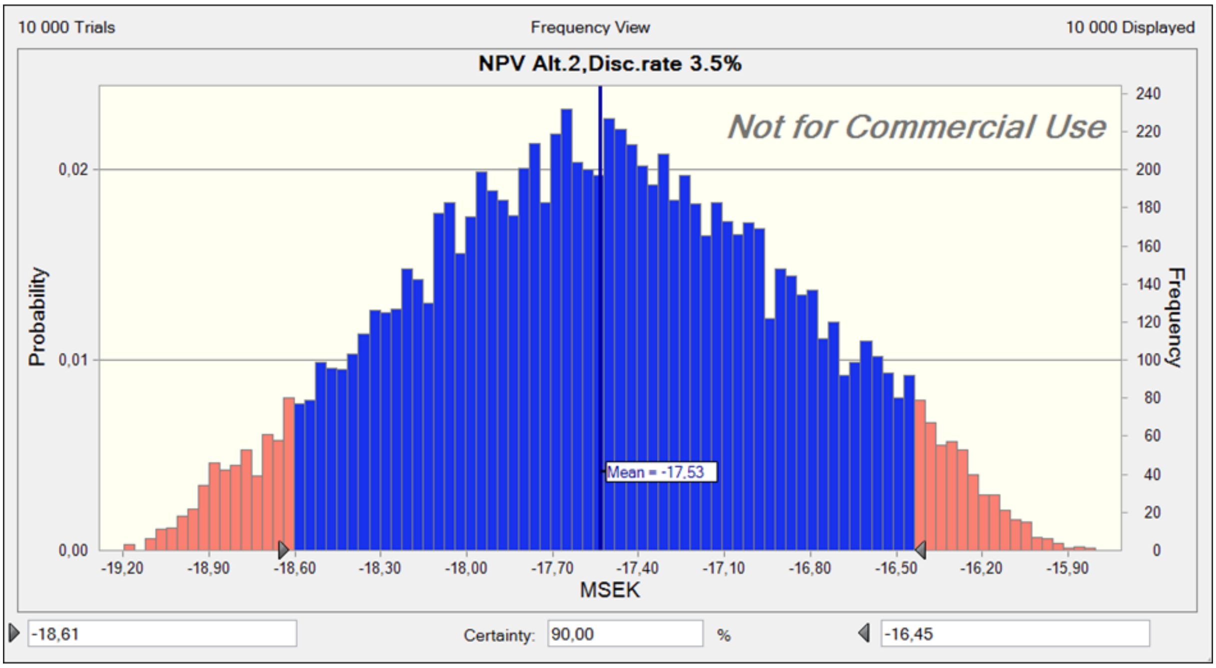

Figure 5.2. Simulation result showing the statistical distribution for NPV in Alternative 2, i.e. excavation and direct landfilling of the soil at NOAH, excavation and incineration of bark and peat in Svenljunga, ash washing in Göteborg, ash residue disposal at NOAH and metal sludge sale to Boliden.. See Table 3.1 for overview of alternatives.

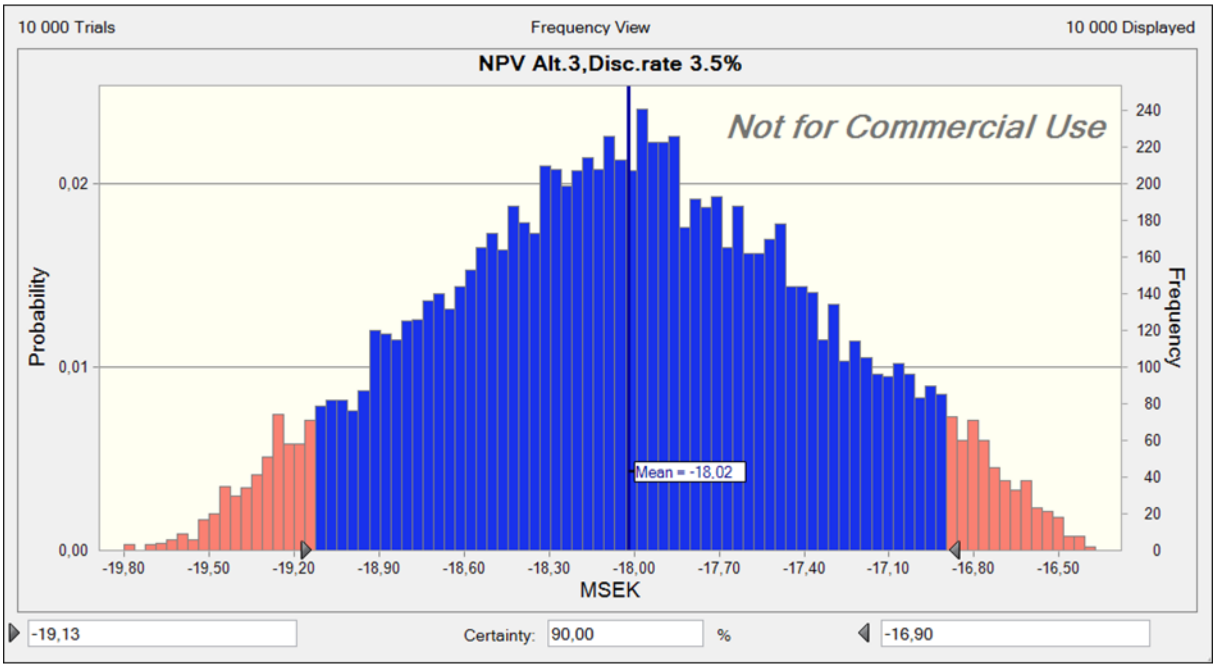

Figure 5.3. Simulation result showing the statistical distribution for NPV in Alternative 3, i.e. excavation and direct landfilling of the soil at Partille, excavation and incineration of bark and peat in Svenljunga, ash washing in Göteborg, ash residue disposal at Partille and metal sludge sale to Boliden.. See Table 3.1 for overview of alternatives.

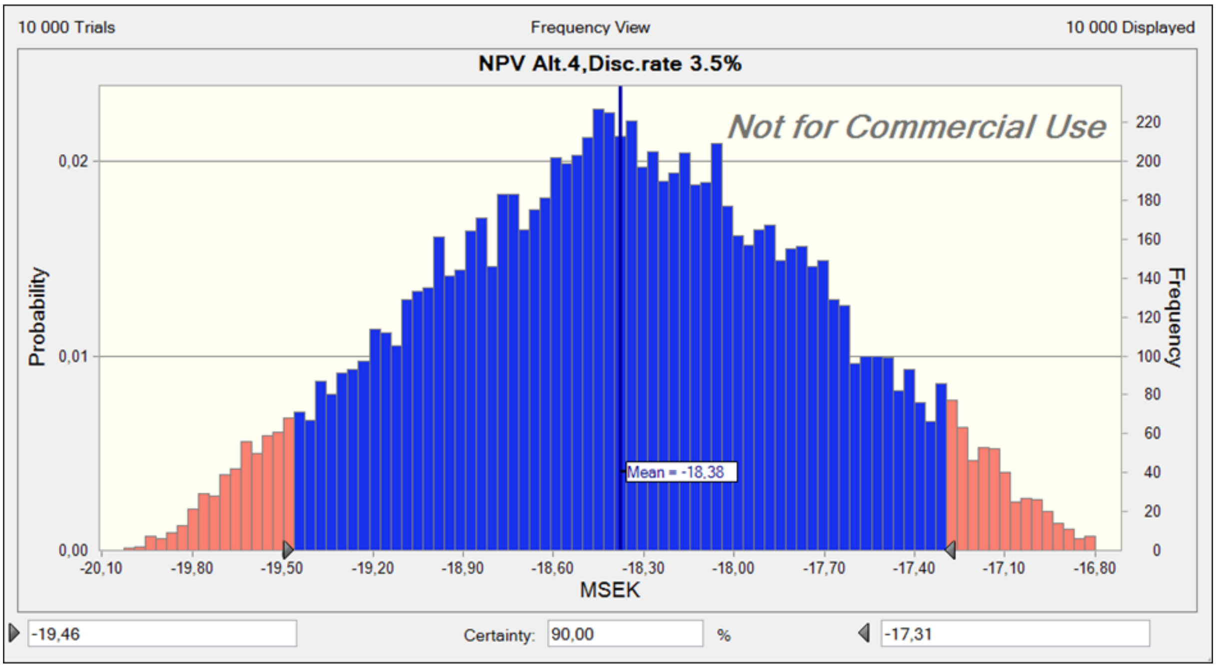

Figure 5.4. Simulation result showing the statistical distribution for NPV for Alternative 4, i.e. excavation and direct landfilling of the soil at NOAH, excavation and incineration of bark and peat in Svenljunga followed by disposal of the ash at Boliden. See Table 3.1 for overview of alternatives.

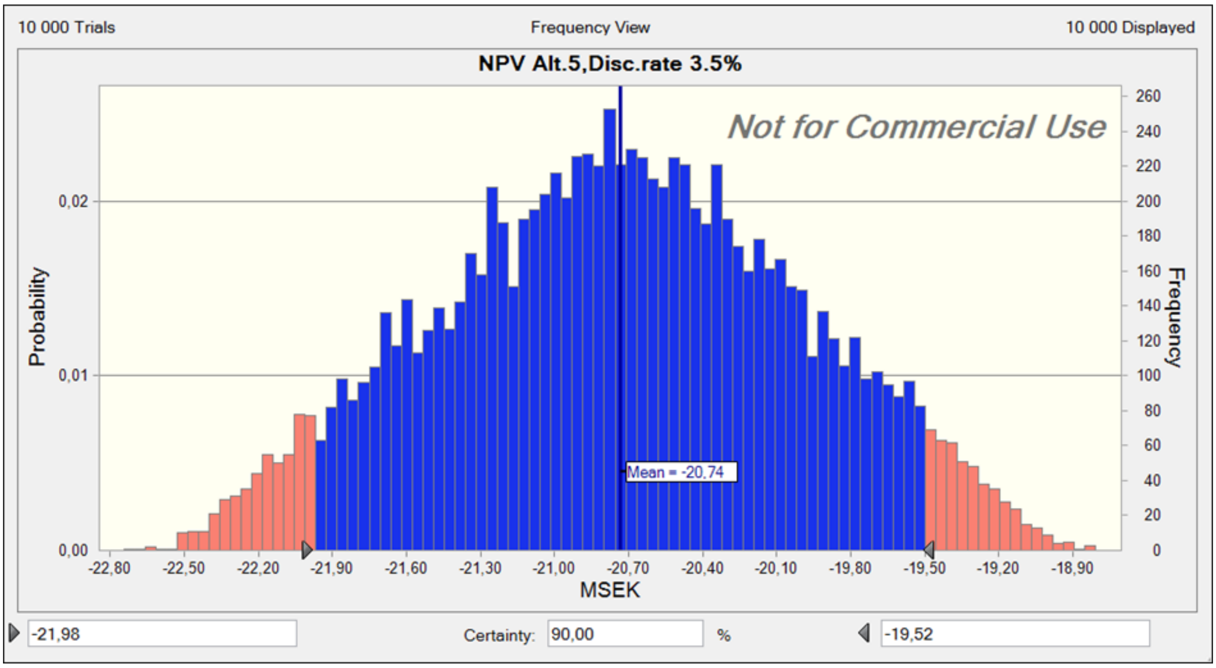

Figure 5.5. Simulation result showing the statistical distribution for NPV in Alternative 5, i.e. excavation and soil washing at Göteborg, excavation and incineration of bark and peat in Svenljunga, ash washing in Göteborg, ash and soil residue disposal at Partille and metal sludge (ash and soil) sale to Boliden.. See Table 3.1 for overview of alternatives.

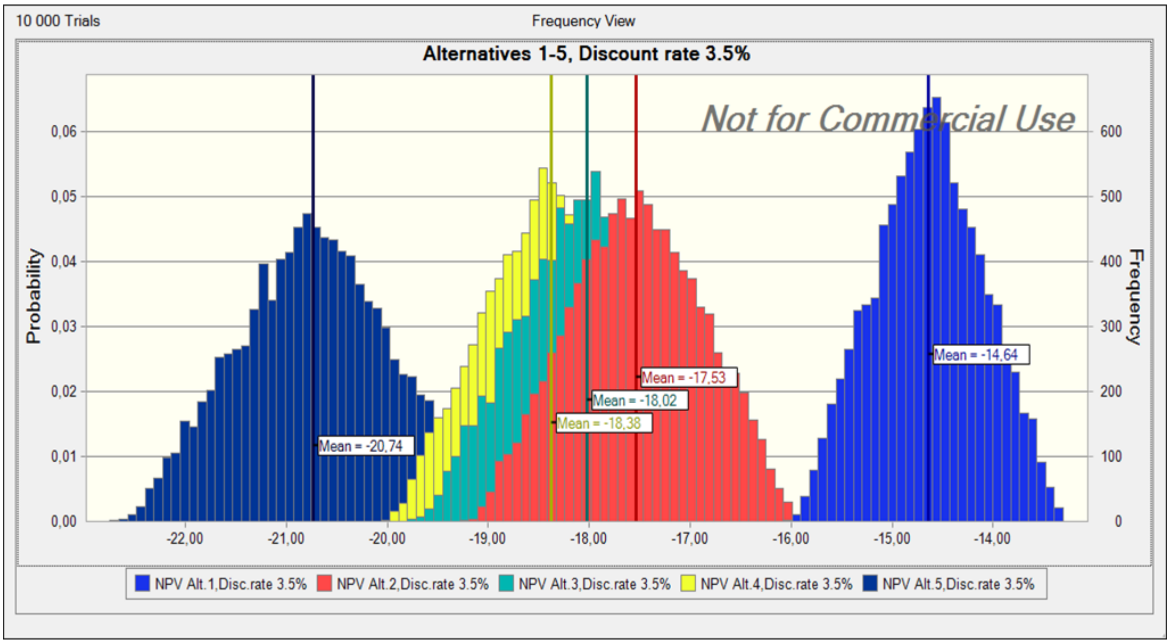

Figure 5.6. An overlay chart showing the statistical distributions of the NPVs for remediation alternatives 1-5.

The sensitivity analysis carried out with Monte Carlos simulation indicated that the uncertain variable Cost of Remedial action, C1d has the largest influence on the uncertainty of the final result, contributing 99.1-95.2-93.6-94.3.6-92.7% to the variance of the forecast for NPV in *Alternatives 1-2-3-4-5* respectively. This cost is sensitive due to the complexity in its different input parameters and associated uncertainty in the amount of contaminated soil, number of transports of contaminated soil, the amount of refilling material, and costs for soil washing which are relevant in *Alternatives 2, 3* and *5* (see Appendix K for details). Moreover, *increased health risk from transportation, C2b*, has also a significant influence on the result in *Alternative 5*. This could be as result of many transportation routes in comparison to other alternatives.

Another type of sensitivity analysis, showing the effects of discount rates on the result, is presented in Table 5.3. The change in discount rates lower discount rate, such as 1.4% and 0% according to Rosén et al. (2008), also indicates negative NPV in all alternatives. None of alternatives is profitable. Still, *Alternative 1* generates the lowest negative NVPs.

Table 5.3 NPVs alternative 1-5 for different discount rate.

Alternative	Discount rate of 3.5 %	R*	Discount rate of 1.4%	R*	Discount rate of 0 %	R*
1	−14.64	1	−14.44	1	−13.77	1
2	− 17.53	2	−17.28	2	−16.57	2
3	− 18.03	3	−17.79	3	−17.08	3
4	− 18.38	4	−18.18	4	−17.51	4
5	− 20.74	5	−20.48	5	−19.77	5

*Ranking of the alternatives.

6. Discussion

Evaluation of the costs and benefits for the remediation project at Långö was time-consuming and also some items are not easy to quantify. Cost category *remedial action*, C1d, has the largest part of the total cost in all the alternatives. *Increased health risk from transportation*, C2b, shows a significant cost effect in the *Alternative 5* as well. Monte Carlo simulations and sensitivity analysis indicated that C1d is the major uncertain cost contributing to variance in the NPV for *Alternatives 1-5*. The significant contribution of cost *C2b* for *Alternative 5* to the total uncertainty compared to other remediation alternatives was due to many routes included in this alternative. The negative effects of remedial action on workers were calculated with help of SADA. The risk of accidents during transportation of masses from and to the site is larger than the risk of worker exposure to harmful levels of contaminants.

The cost for *decreased provision of ecosystem services on site and in the surroundings*, C3a and C3b, were extrapolated from previous studies (Brycke et al., 2013; TrExTool, 2009). The amount of CO_2 emissions that will be generated as result of remediation activities was multiplied by cost for emission per ton provided in SIKA (2009).

The *reduced non-acute health risks*, B2b, is the largest benefit in all the alternatives for the Långö case and it was calculated with SADA and using a Value of Statistical Life (VSL) estimated in a price level of 2006 (SIKA, 2009). However, further research is need to analyse how the CBA outcome is affected if VSL in a price level of 2010 is used in accordance with ASEK (2012). This variable in the CBA is the most sensitive uncertain benefit contributing to variance in the NVP in all the five alternatives. *Increased provision of other ecosystem services*, B3c, estimated by the benefit transfer method has very low influence in the analysis. Finally, the recycling of copper from the excavated masses is a promising alternative to remediate the contaminated soils at Långö. This is important from the environmental point of view as the unused metal resources embedded in deposits at the site can be utilized, while (1) reducing the demand for mining virgin ore, (2) promoting resource use efficiency, and (3) leading to conservation of natural resources. In this thesis, the worth of copper recovered from the deposits at the Långö site was estimated to be 1.5 MSEK.

It is important to stress that some benefits such as *increased recreational opportunities on the site and in the surroundings*, B3a and B3b were unable to be monetized in this study. If these benefits are monetized, they will generally have positive influence in the remediation projects (Söderqvist, et.al, 2015). Rosén et al. (2008) stressed that B3a and B3b are difficult to estimate and such recreation possibilities can be valued economically using one of the environmental valuation methods like the contingent valuation method (CVM) or value transferring (the benefit transfer method). However, valuation methods are usually a time- and budget-consuming process, often including use of questionnaire studies. Moreover, it was not possible to find any similar valuation study site in the database recommended by Rosén et al. (2008) which is suitable for benefit transfer in the Långö case. Concluding, it is difficult, but important to estimate these benefits (B3a and B3b), which have most likely a value above zero.

The eventual result of CBA might be very sensitive to the choice of the discount rate, particularly, when long time horizons are chosen for the project assessment (Söderqvist, et al., 2015). This statement is in line with the sensitivity analysis results for the Långö remediation project (see Table 5.3). A time horizon of 200 years was used to account for long-term reductions in health risks and improved recreational opportunities. Meanwhile, in this thesis study, the application of different discount rates shown to have very slight variation in the NPV for all the alternatives in contrary to Söderqvist, et al. (2015). At a discount rate of 3.5%, 1.4% and 0% the NPV of all remediation alternatives are negative with a slight different of 1MSEK at lower discount rate (see Table 5.3). In theory the choice of discount rate has the greatest influence on social profitability of a remediation alternative. Moreover, CBA strives to monetise all costs and benefits associated with a project. In an environmental project, the NPV result from CBA is always subjected to a debate whether the analysis can be used as a complete decision-making aid, even if CBA has sufficient data required for a complete monetisation. This is due to the intrinsic values of nature, which are not possible to evaluate in economic terms for all environmental issues. According to Hanley et al. (1993), CBA is a useful contribution to the decision-making process but it is not sufficient as the single criterion. It should be complemented with other types of assessments to provide a complete basis for decision-making, e.g. Multi-Criteria Analysis (MCA) (e.g. Rosén et al., 2008, 2013, 2015).

Furthermore, the method used in this thesis for estimation of the copper quantity resulting from soil/ash washing of the contaminated soil at Långö should further be elaborated. Soil washing is common in Europe but despite its popularity sufficient data on the cost of washing is not publicly available. And also to obtain a consistent data on leaching procedure, i.e. it was extremely difficult to estimate in this study how much metal sludge is obtainable from a certain amount of leachate.

7. Conclusions and Recommendation

In this Master's thesis, I attempted to test and evaluate the CBA method in the remediation project assuming recovery of copper from contaminated site. Using the CBA steps developed by Rosén et al. (2008), the study investigates to what extent the NPV of remediation in combination with metal recycling is socially profitable.

The following conclusions were drawn from this study.

- CBA is an important part of the support needed for sound prioritization of remedial actions. However, the method is associated with a lot of uncertainty because to find exact and accurate information about the input data to the CBA is difficult. In this respect, it is very important for decision-makers to emphasize on the items that are contributing most to NPV uncertainty in order to make the assessment reliable when making a choice among the remediation alternatives.

- The overall outcome of this study shows that from a purely economic perspective it is not worthwhile to recycle metals from contaminated soil during remediation. Thus; if recycling should be done, then *Alternative* 2 which assume excavation and direct landfilling of the soil at NOAH, excavation and incineration of bark and peat in Svenljunga, ash washing in Göteborg, ash residue disposal at NOAH and metal sludge sale to Boliden, is the most reasonable option among alternatives assuming metal recycling. However, *Alternative 1,* i.e. excavation, incineration of bark and peat, disposal of the ash and contaminated mineral soil at NOAH assuming no metal recycling, is the most cost effective remediation alternative. This alternative has the lowest *decreased provision of ecosystem services in the surroundings*, i.e. CO_2 emissions from transportation and *other negative externalities than C2 and C3,* i.e. noise and air pollution. But from the resource recovery point of view, *Alternative 1* is the worst among other alternatives. Therefore, *Alternative 1* requires further analysis to evaluate its potential toward being a sustainable remediation option e.g. using Multi-Criteria Analysis (MCA).

- Moreover, it is also very important to stress the effect of the transportation cost of masses from and to the site. In the cost assessment for *remedial action,* C1d, cost of transporting masses from Långö to off-site treatment location, to disposal location and the mining and smelting company represents the largest part of the total cost in remediation action. It would be interesting to carry out a further research of metal recycling from contamination site in respect to close proximity between the contaminated site and the mining company.

- Monte Carlo simulation is very useful tool to evaluate the uncertainty in the assessment results. All uncertainties that are not included in the uncertainty analysis are likely to contribute to a significant degree of variation than what the statistical NPV distributions have shown in this analysis.

- A CBA cannot provide all support needed for decision-making. Still, the answers it provided are extremely valuable playing an important role in ranking between the remediation alternatives. Thus, CBA is concluded to be a valuable method that can be used as a decision-support tool prioritizing between the remediation alternatives.

- Finally, to achieve a comprehensive assessment of metal recycling from the contaminated soil, it is important to study cost and benefit items which were not monetized in this study as well as revise those items where Value of statistical life (VSL) was used for calculations. The recent VSL according STA, 2012 should be considered for a more accurate estimation in the future study. Furthermore, it is also important to evaluate the total energy consumption from the precipitation procedure for generating the metal sludge in comparison to mining of virgin ore.

References

Andersson, D., Lundsröm, J., 2015. *Enhanced Soil Washing: A Study on Treatment of Copper Polluted Soil and Bark.* Department of Civil and Environmental Engineering, Chalmers University of Technology, Göteborg.

Bridge, D., 2004. *CONTESTED TERRAIN: Mining and the Environment.* Annu.Rev.Environ. Resour. 2004. 29:205-59. Doi: 10.1146/annurev.energy. 28 .0111503.163434. Department of Geography, Syracuse University, Syracuse.

Brinkhoff, P., 2014. *Economic Project Risk Assessment for sustainable Choice of REmediation (SCORE) in Construction Projects*. Chalmers University of Technology.

Burgman, M., 2005. *Risks and Decisions for Conservation and Environmental Management.* Cambridge University Press. ISBN: 9780511614279

EC, European Commission, 2006. *GUIDANCE ON THE METHODOLOGY FOR CARRYING OUT COST-BENEFIT ANALYSIS*. Working Document No. 4

Elander Miljöteknik AB, 2014. *Efterbehandling av f.d. impregneringsplats på Långö, Köpmannebro i Melleruds kommun, Förstudie avseende möjligheterna att återvinna koppar från förorenade massor.* Uppdrag: 1401

Eriksson, A., Johansson, P., 2013. *Soil Washing: Optimization of Acid Leaching of Copper from Contaminated Soil.* Master's Thesis 2013:32. Department of Civil and Environmental Engineering, Chalmers University of Technology, Göteborg.

Garrod, G., Willis, K.-G., 1999. *Economic Valuation of the environment and case study method.*

Hanley, N., Barbier, E-B., 2009. *PRICING NATURE, Cost-Benefit Analysis and Environmental Policy.* ISBN 978 1 84542 789 4

Hanley, N., Spash, C-L., 1993. *COST-BENEFIT ANALYSIS and the ENVIRONMENT.* ISBN 1 85278 455 5

Kemakta Konsult AB,2012. *Kompletterande huvudstudie för förorenad mark vid f.d. stolpimpregnering på Långö, Köpmannebro, Mellerud kommun.*

Hasler, B., Lundhede, T., Martinsen, L., Neye, S., Schou, J-S., 2005. *Valuation of groundwater protection versus water treatment in Denmark by Choice Experiments and Contingent Valuation.* National Environmental Research Institute. NERI Technical Report No. 543(2005). ISSN (electronic):1600-0048

Hasselström, L., Johansson, K., Kinell, G.,Soutukorva, Å., Söderqvist, T., 2014. Värdet av vattenkvalitetsförbättringar i Sverige- en studie baserad på värdeöverföring. Enveco rapport 2014:1

Jerksjö, M., Fridell, E., 2009. TrExTool, *Manual for tool for calculation of external costs for goods transports*. IVL Swedish Environmental Research Institute.

Karlfeldt Fedje, K., Yillin, l., Strömvall, A-M., 2013. *Remediation of metal polluted hotspot areas through enhanced soil washing -Evaluation of leaching methods.* Journal of Environmental Management 128 (2013) 489-496.

Kemakta AR 2012-06. *Kompletterande huvudstudie för förorenad mark vid f.d. stolpimpregnering på Långö, Köpmannebro, Mellerud kommun.*

Kriström, B., Bonta Bergman, M., 2014. *Samhällsekonomiska analyser av miljöprojekt – en vägledning.* Naturvårdsverket rapport 6628 (2014) ISBN 978-91-620-6628-4. ISSN 0282-7298 Sveriges lantbruksuniversitet, Umeå.

Landström, Å., Östlund, A.-S., 2011. *Choosing Sustainable Remediation Alternatives at Contaminated Sites: Application and Evaluation of a Multi-criteria Analysis Method*. Master's Thesis 2011:110. Department of Civil and Environmental Engineering, Chalmers University of Technology, Göteborg.

Oracle, 2010. [Electronic] *Oracle Crystal Ball. Version: 11.1.2.4*
Available at:
http://www.oracle.com/technetwork/middleware/crystalball/downloads/index.html

Pearce, D., Atkinson, G., Mourato, S., 2006. *Cost-Benefit Analysis and the Environment.* RECENT DEVELOPMENT. OECD PUBLISHING.

Pettersson, A., Karlfeldt Fedje, K., Anderssson, S., Modin, O., Frändegård, P., 2013. *Metallutvinning med fokus på Zn från avfallsflygaska med hjälp av sura processvatten.* WASTE REFINERY, WR-58. ISSN 1654-4706

Rinaudo, J.-D., Aulong, S., 2013. *Defining Groundwater Remediation Objectives with Cost-benefit Analysis: Does It Work?* Water Resource Manage (2014) 28:261–278. DOI 10.1007/s11269-013-0483-0.

Rosén, L., Back, P-E., Soutukorva, Å., Söderqvist, T., Brodd, P., Grahn, L. 2008. *Kostnads-nyttoanalys som verktyg för prioritering av efterbehandlingsinsatser-metodutveckling och exempel på tillämpning.* Naturvårdsverket rapport 5836 (2008). ISBN 978-91-620-5836-4.pdf ISSN 0282-7298.

Rosén, L., Norrman, J., Norberg, T., Volchko, Y., Söderqvist, T., Back, P-E., Norin, M., Bergknut, M., Döberg, G., 2013. *SCORE: Multi-Criteria Analysis (MCA) for Sustainability Appraisal of Remedial Alternatives.* Bioremediation and Sustainable Environmental Technologies—2013. ISBN 978-0-9819730-7-4.

Rosén, L., Back, P-E., Söderqvist, T., Norrman, J., Brinkhoff, P., Norberg, T., Volchko, Y., Norin, M., Bergknut, M., Döberl, G., 2015. *SCORE: A novel multi-criteria decision analysis approach to assessing the sustainability of contaminated land remediation.* Science of the Total Environment 511(2015) 621-638.

SADA, 2007. [Electronic] *Spatial Analysis and Decision Assistance, SADA version 4.1* The University of Tennessee, Knoxville. Available at: http://www.sadaproject.net/download.html

SIKA, Statens institut för kommunikationsanalys, 2009. *Värden och metoder för transportsektorns samhällsekonomiska analyser – ASEK 4.* ISSN 1402-6651.

STA, Swedish Transport Administration (2012). Samhällsekonomiska principer och kalkylvärden för transportsektorn: ASEK 5.2. Available at: http://www.trafikverket.se/contentassets/13c6f625c3324bc4b34a59c9f4594703/09_trafiksakerhet_a52.pdf [Accessed 28 October 2015]

Strömberg, B., Svärd,S-H., 2012. *ANLÄGGNINGS- OCH FÖRBRÄNNINGSTEKNIK 1234. Bränslehandboken 2012.* Värmeforsk.

Swedish Environmental Protection Agency, 2013. *Samhällsekonomisk analys av etappmål för efterbehandling av förorenade områden.* NV-00336-13 [pdf] Available at: http://www.naturvardsverket.se/upload/miljoarbete-i-samhallet/miljoarbete-i-sverige/regeringsuppdrag/2013/etappmal2013forslag/etappmal2013forslag-ebh-samh-analys.pdf[Accessed 27 October 2015]

Swedish Environmental Protection Agency, 2012. SWEDEN'S ENVIRONMENTAL OBJECTIVES-AN INTRODUCTION [pdf] Available at: http://www.naturvardsverket.se/Documents/publikationer6400/978-91-620-8620-6.pdf?pid=6759 [Accessed 13 February 2015] ISBN 978-91-620-8620-6.

Söderqvist, T., Brinkhoff, P., Tommy Norberg, T., Rosén, L., Back, P-E., Norrman, J., 2015. *Cost-benefit analysis as a part of sustainability assessment of remediation alternatives for contaminated land.* Journal of Environmental Management 157 (2015) 267-278.

THE EUROPEAN OPINION RESEARCH GROUP (EORG), 2002.*The attitudes of Europeans towards the environment.* [Pdf] Available at: http://ec.europa.eu/public_opinion/archives/ebs/ebs_180_en.pdf [Accessed 30 April 2015]

WRI, World Resource Institute, 2003. *MINING AND CRITICAL ECOSYSTEMS: Mapping* the *Risks.* ISBN: 1-56973-554-9.

Appendices

Appendix A. Calculations of the soil and ash amounts

According to Kemakta (2012) the masses are very wet represented by 6 600 tons of bark and 630 tons of peat. These amounts will be excavated and transported for further treatment/landfilling. However, the dry content of the masses is considered for incineration. Calculations for dry contents are based on assumptions summarized below[16].

Bark

Copper concentration is 13 700mg/kg and the total amount of copper present in the bark is 26 ton. Thus,

1 kg bark gives 0.0137 kg copper,

1 897 810kg bark gives 26 000 kg copper.

Therefore, 1 898 tons is the dry amount of bark to be incinerated.

Peat

Copper concentration is 18 300mg/kg and the total amount of copper present in the peat is 5 ton. Thus,

1 kg peat gives 0.0183 kg copper,

273 224 kg gives 5000 kg copper.

Therefore, 273 tons are the dry amount of peat to be incinerated.

Clay

Copper concentration is 1 800 mg/kg and the total amount of copper present in the clay is 2 ton. Thus;

1kg clay gives 0.0018 kg copper,

1 111 111 kg clay gives 2 000 kg copper.

Therefore, 1 111 ton is the dry amount of clay considered when estimating required process water.

Glacial till

[16] Karin Karlfeldt Fedje, supervision meeting. 2015-05-27

Copper concentration is 4 500 mg/kg and the total amount of copper present in the glacial till is 2 tons. Thus,

1 kg fine particle glacial till gives 0.0045 kg copper,

444 444kg fine particle glacial till will give 2 000 kg copper.

Therefore, 444 tons are the dry amount of glacial till considered when estimating required process water.

Appendix B. Calculation of NaOH amount

Assume, pH leachate before and after precipitation are 0.5 and 9 respectively.

pH = -log(H_3O^+) ↔ (H_3O^+) = 10^{-pH}

pH (log$10^{-0.5}$ - log10^{-9})= 0.3162 mol

Using the molarity formula

C= n/v,

where C= Molar concentration (mol/L),

n = Amount of solute in mole (g),

v = Volume of solution (L),

molar mass of NaOH is calculated as (23+16+1) = 40g/mol.

Thus, 1 gram of NaOH per 1 L of leachate equals to

C = n/v,

(0.3162 mol* 40g/mol) = n/ 1L,

n = 12.648g.

Thus, 14.2 tons of NaOH is required to produce 1 121 tons of leachate. .

Appendix C. Time horizon, remediation at Långö[17]

	Years															
Benefits	1	2	3	4	5	6	7	8	9	10	20	40	60	80	100	200
B2b. Reduced chronic(non-acute) health risks																
B3c. Increased provision of other ecosystem services																
B5. Recycling of metals																
Costs																
C1d. Remedial action																
C1e. Monitoring																
C2a. Increased health risks on site																
C2b. Increased health risks from transport activities																
C3a. Decreased provision of ecosystem services on site																
C3b. Decreased provision of ecosystem services in the surroundings																
C4. Other negative externalities than C2 and C3																

[17] Developed in consultation with Yevheniya Volchko.

Appendix D. Willingness-to-pay for improved groundwater quality

WTP to improve groundwater quality in Långö was calculated through benefit transfer using two valuation studies from Denmark and France. WTP to purified water in Denmark was 529DKK/household/year (in 2004 DKK) and WTP for Groundwater Protection in Rhine valley aquifer, France was €42 /household/year (in 2006 Euro).

To use benefit transfer from these two studies, GDP ratio between each country and Sweden must be estimated for first so as to correct WTP for policy site (Långö). Thus, calculation is based on the formula below (Kriström & Bonta Bergman, 2014).

WTP for policy site (WTP_{policy})

$WTP_{policy} = WTP_{study} (Y_{policy} / Ystudy)$,

Where WTP_{study} is a value estimate for the original site (study site 1),

Y_{study} is income levels for the study site,

Y_{policy} is income levels for the policy site (the Långö site).

Value transferring from Danish study

GDP per capita in Sweden (2004) is 42 442.3 U.S. Dollars[18].

GDP per capita in Denmark (2004) is 46 487.8 U.S. Dollars[19].

42 442.3/46 487.8 = 0.9

GDP ratio (2004) = 0.9

529 DKK was equivalent to 646 SEK in June 2004[20].

WTP for household/year corrected for income is

646 * 0.9 = 590 SEK in 2004.

WTP in 2015 for improved groundwater quality at Långö transferred from the study site 1 (Denmark) is

$590 + 590*0.12_{(\text{inflation rate})}$[21] = 661 SEK/per household/year.

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18 http://data.worldbank.org/indicator/NY.GDP.PCAP.CD?page=1

19 http://data.worldbank.org/indicator/NY.GDP.PCAP.CD?page=1

20 www.valuta.se

21 http://www.scb.se/sv_/Hitta-statistik/Statistik-efter-amne/Priser-och-konsumtion/Konsumentprisindex/Konsumentprisindex-KPI/33772/33779/Konsumentprisindex-KPI/33831/

Value transferring from French study

GDP per capita in Sweden (2006) is 46 256.2 U.S. Dollars[22].

GDP per capita in France (2006) is 36 544.6 U.S. Dollars[23].

46 256.2/36 544.6= 1.2657

GDP ratio (2004) = 1.2657

42 Euros was equivalent to 389 SEK in June 2006[24]. .

WTP for household/year corrected for income is

389 *1.2657 = 492 SEK in 2006.

WTP in 2015 for improved groundwater quality at Långö from the study site 2 (France) is

492 + 492*0.11$_{\text{(inflation rate)}}$ = 547 SEK/per household/year.

WTP for improved groundwater at the Långö site

Thus, the average of the two estimated values is the estimated WTP for improved groundwater quality at Långö:

$\text{WTP}_{\text{Långö}} = \frac{661+547}{2} = 604$ SEK/per household/year.

$\text{WTP}_{\text{Långö 5 households}}$ = 5 * 604= 3 020 SEK/year.

Reference

Kriström, B., Bonta Bergman, M., 2014. *Samhällsekonomiska analyser av miljöprojekt – en vägledning.* Naturvårdsverket rapport 6628 (2014) ISBN 978-91-620-6628-4. ISSN 0282-7298 Sveriges lantbruksuniversitet, Umeå.

22 http://data.worldbank.org/indicator/NY.GDP.PCAP.CD?page=1

23 http://data.worldbank.org/indicator/NY.GDP.PCAP.CD?page=1

24 www.valuta.se

Appendix E. Increased health risk on the site

In the remediation process workers are subjected to health risks due to their exposure to pollutants and accidents on the site during operation. The workers' health risk levels during excavation was estimated using SADA parameters as shown Table E.1 Some of SADA default values were adjusted to Naturvårdsverket's standard (NV, 2009a), in order to fit assessment to site-specific conditions.

Table E.1 Default Exposure parameters in SADA with adjusted values according to Naturvårdsverket for increased health risk on the site.

SADA parameters	**Adjusted**	**Default**	**Units**	**Reference**
Risk taget (one out of 100 000)	**0,00001**	**0,000001**		
Screening statistics	**UCL95**	**Max**		
Exposure statistics	**UCL95**	**Max**		
Excavation Soil Scenario				
Adherence factor		1	mg/cm2	
Adult Body Weight		70	kg	
Adult Exposure Duration		1	yr	
Adult Soil Ingestion Rate	20	480	mg/day	NV (2009)
Adult Surface Area		0,53	m2/day	
Child Body Weight		15	kg	
Child Exposure Duration		0	year	
Child Soil Ingestion Rate		0	mg/day	
Exposure Frequency	200	20	day/year	NV (2009)
Fraction Ingested		1	unitless	
Gamma exposure time factor		0,3333	hr/hr	
Gamma shielding factor		0,2	unitless	
Total Inhalation Rate		20	m3/day	
Life Time	80	70	year	NV (2009)
Exposure Duration		1	year	

Table E.2 Risk levels due to excavation on site calculated with help of SADA.

Contaminant/Scenarios/ exposure pathway	CAS Number	*Conc.*	*Ingestion*	*Inhalation*	*External*	Total (∑)
Copper(Cu64) /Excavation/Soil	13981254	10722.484	7.4E-7	1.4E-10	1.3E-2	**1.3E-2**
Lead(Pb200)/Excavation/ Soil	40315	545.259	8.8E-06	1.9E-11	4.80E-4	**4.89E-4**

The cost for the health risk measure on the site is calculated using this Eq. E.1:

$$C_{\text{health risk on site}} = \frac{(VSL \times n \times \sum Risk)}{t}, \qquad \text{(Eq.E.1)}$$

where *VSL* = 21 MSEK (Value of statistical life)[25],

n = 10 (assumed number of workers on the site for excavation) (Landström and Östlund (2011)),

t = 1 year (Adult exposure duration).

Calculation of costs associated with increased health risk on site

$$C_{\text{health risk on the site (Copper)}} = \frac{0.37 \times (21000000 \times 10 \times 1.3E{-}02)}{1} = 2.73\ MSEK$$

$$C_{\text{health risk on the site (Lead)}} = \frac{0.37 \times (21000000 \times 10 \times 4.89E{-}4)}{1} = 0.1027\ MSEK$$

According to Arbetsmiljöverket (2010), 4.7% represent the average of work-related accidents per year among the workers in construction field. In this respect, the number of workers that is expected to suffer from a work related accident during excavation at the Långö site among 10 workers during 1 year of operation can be calculated as $10 \times 0.047 \times 1 = 0.47$.

According to SIKA (2009), the cost for a person that injured slightly in a traffic accident is 199 000 SEK (SIKA, 2009). This value is multiplied by the number of workers that is expected to suffer from a work-related accident during excavation to find the cost for work-related accidents at Långö, i.e.

$C_{\text{work-related accident}} = 199\ 000 \times 0.47 =$ **93 530 SEK**.

Total annual cost for health risks due to the measure on site is

2.73 + 0.1027 + 0.093530 = 2.9262 MSEK.

References

Arbetsmiljöverket,(2010). Arbetsmiljöstatistik Rapport 2010:4. *Arbetsorsakade besvär 2010(Work-Related Disorders 2010).* ISSN 1652-1110

[25] SIKA (2009).

Naturvårdsverket, 2009a. *Riktvärden för förorenad mark. Modellbeskrivning och vägledning.* Report no: 5976. ISBN 978-91-620-5976-7. ISSN 0282-7298

SADA, 2007. [Electronic] *Spatial Analysis and Decision Assistance, SADA version 4.1* The University of Tennessee, Knoxville. Available at: http://www.sadaproject.net/download.html

SIKA, Statens institut för kommunikationsanalys, 2009. *Värden och metoder för transportsektorns samhällsekonomiska analyser – ASEK 4.* ISSN 1402-6651

Appendix F. Probability for traffic accident with contaminated soil

The annual probability for accidents on road with heavy vehicle loaded with contaminated soil, is calculated according to the following formula (Swedish National Road Authority, 2013)

$P_o = 0.1 \times N \times Q \times L \times 365 \times F \times 10^{-6}$,

where N is mean number of transports with heavy vehicle per day,

Q is number of accidents/million transport kilometres [1],

L is road length [km],

F is number of vehicles per accidents [1.5].

Probability of soil release due to accident is P_u=0.03.

Calculations of annual risk cost

It is assumed that the number of people involved in an accident is 1.5 and the cost of getting severe damages will then be 4 147 000 SEK/person (SIKA Rapport, 2009). The assumed amount for a vehicle load is approximately 26 tons. In all the alternatives, 9 different routes were considered and their distances are calculated using www.eniro.se. Excavation costs are based on the study by Landström and Östlund (2011). See Tables F.1 and F.2 for details on risk costs associated with traffic accidents. Number of vehicles per day is calculated with help of the TrExTool.

Table F1. The results from the risk calculations from transportation in Alternatives 1-5.

	Alternative 1	**Alternative 2**	**Alternative 3**	**Alternative 4**	**Alternative 5**
Number of vehicles per day	2,4	2,5	2,5	2,5	3,0
Severe injury (MSEK)	4,147	4,147	4,147	4,147	4,147
Release of cont. soil (tons)	26	26	26	26	26
Excavation cost (MSEK/t)	0,000165	0,000165	0,000165	0,000165	0,000165
Excavation cost total (MSEK/t)	0,000644	0,000644	0,000644	0,000644	0,000644
Probability of accident	**0,005**	**0,193**	**0,196**	**0,183**	**0,436**
Injured persons per accident	**1,5**	**1,5**	**1,5**	**1,5**	**1,5**
Annual Risk cost (cont.)	0,033347	1,199281	1,216451	1,138263	2,710458

References

Eniro. (2015). [Electronic] Eniro – maps. Available at:
http://kartor.eniro.se/vägbeskrivning
Measuring function. [2015-01-28].

Landström, Å., Östlund, A.-S., 2011. Choosing Sustainable Remediation Alternatives at Contaminated Sites: Application and Evaluation of a Multi-criteria Analysis Method. Master's Thesis 2011:110. Department of Civil and Environmental Engineering, Chalmers University of Technology, Göteborg.

SIKA, Statens institut för kommunikationsanalys, 2009. *Värden och metoder för transportsektorns samhällsekonomiska analyser – ASEK 4.* ISSN 1402-6651

Trafikverket,Yt- och grundvattenskydd, 2013. Publikation: 2013:135. ISBN: 978-91-7467-526-9

Appendix G. CO_2 emission on-site and in surroundings

CO_2 emissions on-site

For calculation of CO_2 emissions on-site (emissions due to excavation) (C3a). Data provided in Appendix 1&2 in Brycke et al. (2013) was used as a guide to calculate (1) the expected operating hours for the excavator machine operating 94 700 tons of excavated masses, and (2) the amount of CO_2 emissions generated during the operation. The reference CO_2 emission on-site can be calculated according to following steps:

An excavator is expected to excavate a ton in 0.0084h[26],

Excavation of 94 700 tons requires 80h of excavator operation.

CO_2 emission per hour varies with the size of excavator,

Excavator that weighs >35 tons generates 56 266 g CO_2/h.

Excavator that weighs 22 tons generates 35 009 g CO_2/h.

Thus, the interval representing on-site CO_2 emissions is:

[80h* 35 009 g CO_2/h; 80h* 56 266g/h] = [2.8 ton CO_2; 4.5 ton CO_2].

It is assumed that the excavator weighing 35tons is going to operate on site at Långö[27].

Thus, it is assumed that 4.5 ton of CO_2 emissions will be generated during the on -site measure.

According to SIKA (2009), the cost for CO_2 emissions from a larger project equals to 3.50 SEK/kg = 3 500 SEK/ton. Costs associated with CO_2 emissions on-site for different remediation alternatives are presented in Table G.1.

Table G.1. CO_2 emission on-site at Långö.

Alternative	***Emissions*** ton CO2-equivalents	***Emission costs MSEK/ton***	***Cost MSEK***
1	4.5	0.0035	0.01575
2	4.5	0.0035	0.01575
3	4.5	0.0035	0.01575
4	4.5	0.0035	0.01575
5	4.5	0.0035	0.01575

[26] Brycke. et al., 2013.
[27] Yevheniya Volchko, Chalmers University, 2015-05-06

CO_2 emission in the surroundings

For calculation of CO_2 emissions in the surroundings (emission due to transportation) (C3b), the results TrExTool (2009) and cost for CO_2 emissions provided in SIKA Rapport (2009) were used (see Table G.2).

Table G.2. CO_2 emission in the surroundings.

Alternative	***Emissions*** ton CO2-equivalents	***Emission costs MSEK/ton***	***Cost MSEK***
1	42.6	0.0035	0.149100
2	90.2	0.0035	0.315700
3	79.5	0.0035	0.278250
4	90.5	0.0035	0.316750
5	85.8	0.0035	0.300300

Reference

Brycke,E., Dahlström, L., Haag, A.,Hammarberg, L., 2013. *Beräkning av koldioxidemissioner från efterbehandling av förorenad mark*. Bachelor Thesis. Chalmers University of Technology, Gothenburg, Sweden.

SIKA Rapport, 2009:3. *Värden och metoder för transportsektorns samhällsekonomiska analyser* – ASEK 4. ISSN 1402-6651

Jerksjö, M., Fridell, E., 2009. TrExTool, *Manual for tool for calculation of external costs for goods transports*. IVL Swedish Environmental Research Institute.

Appendix H. Costs associated with other negative externalities

Calculations for other negative externalities than C2 and C3, e.g. noise, NO_x and SO_2 are presented below.

Calculation of emissions is based on the estimate from TrExTool (2009) and SIKA (2009), see Table H.1.

Table H.1. Cost associated with noise, NOx, SO_2 pollution.

C4. Other negative externalities than C2 and C3	**Alt. 1 MSEK**	**Alt. 2 MSEK**	**Alt. 3 MSEK**	**Alt. 4 MSEK**	**Alt. 5 MSEK**
Costs associated with noise due to transportation (TrExTool)	0.0026	0.0159	0.0159	0.0163	0.0187
Costs associated with NOx	0.0682 5	0.09772 5	0.0741	0.0966	0.07027 5
Costs associated with SO2	0.0114	0.0115	0.0069	0.0112	0.0054
Total	**0.0822**	**0.1252**	**0.0969**	**0.1241**	**0.0944**

Reference

Brycke,E., Dahlström, L., Haag, A.,Hammarberg, L., 2013. *Beräkning av koldioxidemissioner från efterbehandling av förorenad mark*. Bachelor Thesis. Chalmers University of Technology, Gothenburg, Sweden.

SIKA Rapport, 2009:3. *Värden och metoder för transportsektorns samhällsekonomiska analyser* – ASEK 4. ISSN 1402-6651

Jerksjö, M., Fridell, E., 2009. TrExTool, *Manual for tool for calculation of external costs for goods transports*. IVL Swedish Environmental Research Institute.

Appendix I. Health risk, reduced chronic health risks

Spatial Analysis and Decision Assistance (SADA version 4.1) was used to analyse the major contaminants present at the site in term of their concentration, exposure and toxicological parameters. In general, five land use scenarios are considered in SADA version 4.1 as thus, residential, recreational, industrial, excavation and agricultural. Reduced chronic health risk on this case site was measured through the recreational land use scenarios by calculating for the two contaminants on the base of the UCL95 for mean value of the contaminated site. While the exposure pathways are grouped into soil-based and groundwater-based exposure pathways. In order to fulfil site-specific conditions of this case study, some of the default value settings in SADA were adjusted using the recommendation values from Naturvårdsverket's standard (NV,2009a) for sensitive land(KM) and the main study on Långö (Kemakta,2012). See Table I.1

Table I.1. Default Exposure parameters in SADA with adjusted values according to Naturvårdsverket and Main study

SADA parameters	**Adjusted**	**Default**	**Units**	**Reference**
Risk target (one out of 100 000)	**0,00001**	**0,000001**		NV (2009a)
Screening statistics	**UCL95**	**Max**		
Exposure statistics	**UCL95**	**Max**		
Recreational Soil Scenario				
Adherence factor		1	mg/cm2	
Adult Body Weight		70	kg	
Adult Exposure Duration	74	24	yr	NV (2009a)
Adult Soil Ingestion Rate	50	100	mg/day	NV (2009a)
Adult Surface Area		0,53	m2/day	
Child Body Weight		15	kg	
Child Exposure Duration		6	year	
Child Soil Ingestion Rate	120	200	mg/day	NV (2009a)
Exposure Frequency	60	40	day/year	Kemakta (2009)
Fraction Ingested		1	unitless	
Gamma exposure time factor		0,041667	hr/hr	
Gamma shielding factor		0,2	unitless	
Total Inhalation Rate		20	m3/day	
Life Time	80	70	year	NV (2009a)
Exposure Duration	74	30	year	NV (2009a)
Recreational GW Scenario				
Adult Body Weight		70	kg	
Adult Total Body Surface Area		1,94	m2	
Life Time	80	70	year	NV (2009a)
Exposure Duration	74	30	year	NV (2009a)

Exposure Frequency	60	7	day/year	Kemakta (2009)
Exposure Time		2,6	hr/day	
Fish Ingestion Rate		0	kg/day	
Fraction Ingested		1	unitless	
Inhalation Rate		20	m3/day	
Water Ingestion Rate	2	0,05	L/day	NV (2009a)
Exposure Frequency Fish	0	350	day/yr	

The SADA's risk level in (reference alternative, R_0) was calculated and compared to the risk levels after measure has been taken (Alternative 1-5, R_1). Each contaminant risk level based on the exposure pathways was estimated. The risks associated with copper (Cu) in the soil and lead (Pb) in groundwater shown a significant positive value, which indicate that their concentrations pose risk to human health. Meanwhile, SADA's calculation for the reduction of risks associated with lead (Pb) in the soil shown a negative value. This interpreted as lead concentration in the soil does not pose risks to human health, which is inconsistent with the previous risk assessment conducted in the main study by Kemakta (2012). It is assumed that the inconsistency could arise from the differences in the toxicological models developed in Swedish EPA and SADA version[28]. Table I.2 below show the SADA risk level (R_0) calculation for the reference alternative for the Långö site.

Table I.2. Risk level R_0 for the reference alternative calculated in SADA for each contaminant and different exposure pathway at the Långö site.

Contaminant/Scenarios/exposure pathway	CAS Number	Conc.	Ingestion	Inhalation	External	**Total R_0**
Copper (Cu 64) /Recreation/Soil	13981254	10722.484	4.9E-5	3.4E-9	3.9E-2	**3.9E-2**
Lead (Pb200) /Recreation/Soil	40315	545.259	5.8E-6	4.6E-10	1.4E-3	**1.4E-3**
Lead (Pb200) /Recreation /Groundwater	40315	669.569	2.2E-4	0	0	**2.2E-4**

The risk level after the measure (R_1) was set to be equal to the risk level target in carcinogenic health effects from a contaminated soil that correspond to 1 person out of 100 000 get cancer during lifetime (NV,2009a).

$R_1 = 10^{-5}$

The annual benefit from reduced chronic health risk is estimated according to Eq. D.2 for each contaminant and their exposure pathway.

$$\boldsymbol{B}_{\textit{chronic health risk}} = \left(\frac{\mathbf{R_o} \times \boldsymbol{n_1}}{\boldsymbol{t_1}} - \frac{\boldsymbol{R_1} \times \boldsymbol{n_1}}{\boldsymbol{t_1}} \right) \times \boldsymbol{VSL} \times \boldsymbol{P}_{mortality} + \left(\frac{\mathbf{R_o} \times \boldsymbol{n_2}}{\boldsymbol{t_2}} - \frac{\boldsymbol{R_1} \times \boldsymbol{n_2}}{\boldsymbol{t_2}} \right) \times \boldsymbol{VSL} \times \boldsymbol{P}_{\boldsymbol{mortality}},$$

[28] Yevheniya Volchko, Chalmers University, 2015-04-30

where n = Total number of houses on the site in the null-alternative,

n_1 = Number of child per household multiply by total number of houses,

n_2 = Number of adult per household multiply by total number of houses,

t_1 = Child exposure duration in null-alternative (years),

t_2 = Adult exposure duration in null-alternative (years),

VSL = Value of a statistical life (SEK),

$P_{mortality}$ = Mortality due to cancer.

Input parameter

There are five houses very close to the contaminated site at Långö and houses are used as summer holiday. It is assumed in this study that in each household have at least a family of 2 adult and 1.8 children which come to stay in the houses in summer time. This benefit supposed that the health risk is reduced for as people in the 5 households on the site in the null-alternative. The value of a statistical life (VSL) in a traffic accident is 21 MSEK (SIKA Rapport, 2009). The probability to actually die of cancer in a healthy risk related work has a mortality of 37% for men during a period of 10 year (Landström & Östlund, 2011).

$n = 5$

$n_1 = 1.8 \times 5 = 9$

$n_2 = 2 \times 5 = 10$

$t_1 = 6$ years

$t_2 = 74$ years

$VSL = 21$ MSEK

$P_{mortality} = 37\%$

Calculations

Annual benefit from health risk reduction of Copper in the soil

$B_{Cu\ in\ soil} =$

$$\left(\frac{3.90\text{E}{-02}\times 9}{6} - \frac{1.0\text{E}{-05}\times 9}{6}\right)\times 21000000\times 0.37 + \left(\frac{3.90\text{E}{-02}\times 10}{74} - \frac{1.0\text{E}{-05}\times 10}{74}\right)\times 21000000\times 0.37 = \mathbf{0.9907\ MSEK}$$

$B_{Pb\ in\ soil} =$

$$\left(\frac{\mathbf{1.4E{-}03} \times 9}{6} - \frac{1.0\mathrm{E}{-}05 \times 9}{6} \right) \times 21000000 \times 0.37 + \left(\frac{\mathbf{1.4E{-}03} \times 10}{74} - \frac{1.0\mathrm{E}{-}05 \times 10}{74} \right) \times 21000000 \times 0.37 = \mathbf{0.0353\ MSEK}$$

$B_{Pb\ in\ GW}$ =

$$\left(\frac{\mathbf{2.2E{-}04} \times 9}{6} - \frac{1.0\mathrm{E}{-}05 \times 9}{6} \right) \times 21000000 \times 0.37 + \left(\frac{\mathbf{2.20E{-}04} \times 10}{74} - \frac{1.0\mathrm{E}{-}05 \times 10}{74} \right) \times 21000000 \times 0.37 = \mathbf{0.0108\ MSEK}$$

The total annual benefit from reduction of chronic health risks

The total benefit from eliminating the contaminants from the site and reduce the amount of lead present in the groundwater is summed up as state below, since the contaminants are independent of each other.

0.9907 + 0.0353 +0.0108 = 1.0368 MSEK

References

Kemakta AR 2012-06. *Kompletterande huvudstudie för förorenad mark vid f.d. stolpimpregnering på Långö, Köpmannebro, Mellerud kommun.*

Landström, Å., Östlund, A., 2011. *Choosing sustainable remediation alternatives at contaminated sites: Application and Evaluation of a Multi-Criteria Analysis method.* Master's Thesis 2011:110, Chalmers University of Technology, Gothenburg, Sweden.

Naturvårdsverket, 2009a. *Riktvärden för förorenad mark. Modellbeskrivning och vägledning.* Report no: 5976. ISBN 978-91-620-5976-7. ISSN 0282-7298

Rosén, L., Erik Back, P., Soutukorva, Å., Söderqvist, T., Brodd, P., Grahn, L., 2008. *Kostnads-nyttoanalys som verktyg för prioritering av efterbehandlingsinsatser:Metodutveckling och exempel på tillämpning.* Naturvårdsverket Rapport 5836: June 2008. ISBN 978-91-620-5836-4.pdf. ISSN 0282-7298

SADA, 2007. [Electronic] *Spatial Analysis and Decision Assistance, SADA version 4.1* The University of Tennessee, Knoxville. Available at: http://www.sadaproject.net/download.html

SIKA, Statens institut för kommunikationsanalys, 2009. *Värden och metoder för transportsektorns samhällsekonomiska analyser – ASEK 4.* ISSN 1402-6651

Appendix J. Distributions in Monte Carlo simulation

The likeliest values are equal to the ones calculated before the simulation. The min and max values for the triangular distributions of most cases were calculated as follows: 0.9*likeliest/likeliest/1.1*likeliest (Oracle, 2009).

Table J.1. Distributions for cost and benefit items valid for Alternative 1.

Assumption	**Unit**	**Distribution**	**Min/Likeliest/Max**
C1d. Remedial action	MSEK	Triangular	11.72556/13.0284/14.33124
C1e. Monitoring	MSEK	Triangular	0.40635/0.4515/0.49665
C2a. Increased health risks on site	MSEK	Triangular	0.99279/1.1031/1.21341
C2b. Increased health risks from transport activities	MSEK	Triangular	0.02898/0.0322/0.03542
C3a.Decreased provision of ecosystem services on site	MSEK	Triangular	0.01368/0.0152/0.01672
C3b.Decreased provision of ecosystem services in the surroundings	MSEK	Triangular	0.13419/0.1491/0.16401
C4.Other negative externalities than C2 and C3, e.g. noise and air pollutants(NOx and SO2)	MSEK	Triangular	0.07146/0.0794/0.08734
B2b. Reduced chronic (non-acute)health risks	MSEK	Triangular	0.12537/0.1393/0.15323
B3c.Increased provision of other ecosystem services	MSEK	Triangular	0.07488/0.0832/0.09152
B5.Other benefits (metal recycling)	MSEK	Triangular	0.0000/0.0000/0.0000

Table J.2. Distributions for cost and benefit items valid for Alternative 2.

Assumption	Unit	Distribution	Min/Likeliest/Max
C1d. Remedial action	MSEK	Triangular	14.1858 /15.762 /17.3382
C1e. Monitoring	MSEK	Triangular	0.40635 /0.4515 /0.49665
C2a. Increased health risks on site	MSEK	Triangular	0.99279 /1.1031 /1.21341
C2b. Increased health risks from transport activities	MSEK	Triangular	1.04283 /1.1587 /1.27457
C3a.Decreased provision of ecosystem services on site	MSEK	Triangular	0.01368 /0.0152/ 0.01672
C3b.Decreased provision of ecosystem services in the surroundings	MSEK	Triangular	0.2745 /0.305 /0.3355
C4.Other negative externalities than C2 and C3, e.g. noise and air pollutants(NOx and SO2)	MSEK	Triangular	0.10881 /0.1209 /0.13299
B2b. Reduced chronic (non-acute)health risks	MSEK	Triangular	0.12537 /0.1393 /0.15323
B3c.Increased provision of other ecosystem services	MSEK	Triangular	0.07488 /0.0832 /0.09152
B5.Other benefits (metal recycling)	MSEK	Triangular	1.05021 /1.1669 /1.28359

Table J.3. Distributions for cost and benefit items valid for Alternative 3.

Assumption	**Unit**	**Distribution**	**Min/Likeliest/Max**
C1d. Remedial action	MSEK	Triangular	14.68152/ 16.3128 /17.94408
C1e. Monitoring	MSEK	Triangular	0.40635 /0.4515 /0.49665
C2a. Increased health risks on site	MSEK	Triangular	0.99279 /1.1031 /1.21341
C2b. Increased health risks from transport activities	MSEK	Triangular	1.05777 /1.1753/ 1.29283
C3a.Decreased provision of ecosystem services on site	MSEK	Triangular	0.01368/ 0.0152/ 0.01672
C3b.Decreased provision of ecosystem services in the surroundings	MSEK	Triangular	0.24192/ 0.2688/ 0.29568
C4.Other negative externalities than C2 and C3, e.g. noise and air pollutants(NOx and SO2)	MSEK	Triangular	0.08433 /0.0937 /0.10307
B2b. Reduced chronic (non-acute)health risks	MSEK	Triangular	0.12537 /0.1393 /0.15323
B3c.Increased provision of other ecosystem services	MSEK	Triangular	0.07488 /0.0832 /0.09152
B5.Other benefits (metal recycling)	MSEK	Triangular	1.05021/ 1.1669/ 1.28359

Table J.4. Distributions for cost and benefit items valid for Alternative 4.

Assumption	**Unit**	**Distribution**	**Min/Likeliest/max**
C1d. Remedial action	MSEK	Triangular	13.95846/ 15.5094 /17.06034
C1e. Monitoring	MSEK	Triangular	0.40635 /0.4515 /0.49665
C2a. Increased health risks on site	MSEK	Triangular	0.99279 /1.1031 /1.21341
C2b. Increased health risks from transport activities	MSEK	Triangular	0.98982 /1.0998 /1.20978
C3a.Decreased provision of ecosystem services on site	MSEK	Triangular	0.01368 /0.0152 /0.01672
C3b.Decreased provision of ecosystem services in the surroundings	MSEK	Triangular	0.2754 /0.306 /0.3366
C4.Other negative externalities than C2 and C3, e.g. noise and air pollutants(NOx and SO2)	MSEK	Triangular	0.10791 /0.1199 /0.13189
B2b. Reduced chronic (non-acute)health risks	MSEK	Triangular	0.12537/ 0.1393 /0.15323
B3c.Increased provision of other ecosystem services	MSEK	Triangular	0.07488 /0.0832 /0.09152
B5.Other benefits (metal recycling)	MSEK	Triangular	0.000/.0.000/0.000

Table J.5. Distributions for cost and benefit items valid for Alternative 5.

Assumption	Unit	Distribution	Min/Likeliest/max
C1d. Remedial action	MSEK	Triangular	16.01163/17.7907/19.56977
C1e. Monitoring	MSEK	Triangular	0.40635/0.4515/0.49665
C2a. Increased health risks on site	MSEK	Triangular	0.99279/1.1031/1.21341
C2b. Increased health risks from transport activities	MSEK	Triangular	2.35692 /2.6188 /2.88068
C3a.Decreased provision of ecosystem services on site	MSEK	Triangular	0.01368 /0.0152 /0.01672
C3b.Decreased provision of ecosystem services in the surroundings	MSEK	Triangular	0.26118 /0.2902 /0.31922
C4.Other negative externalities than C2 and C3, e.g. noise and air pollutants(NOx and SO2)	MSEK	Triangular	0.08208 /0.0912 /0.10032
B2b. Reduced chronic (non-acute)health risks	MSEK	Triangular	0.12537 /0.1393 /0.15323
B3c.Increased provision of other ecosystem services	MSEK	Triangular	0.07488 /0.0832 /0.09152
B5.Other benefits (metal recycling)	MSEK	Triangular	1.260/1.400/1.540

Appendix K. Sensitivity Analysis of the Economic Assessment Results

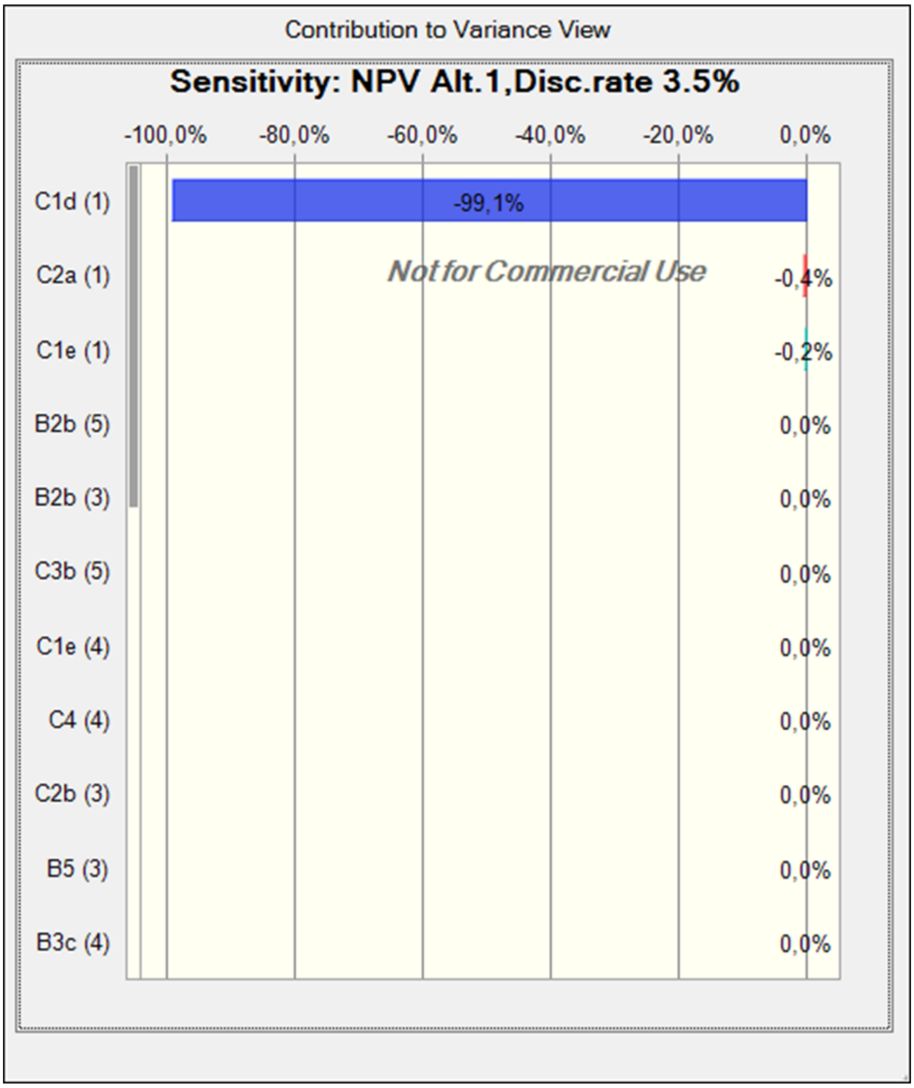

Figure J.1. Results of sensitivity analysis for Alternative 1. Discount rate is set to 3.5%.

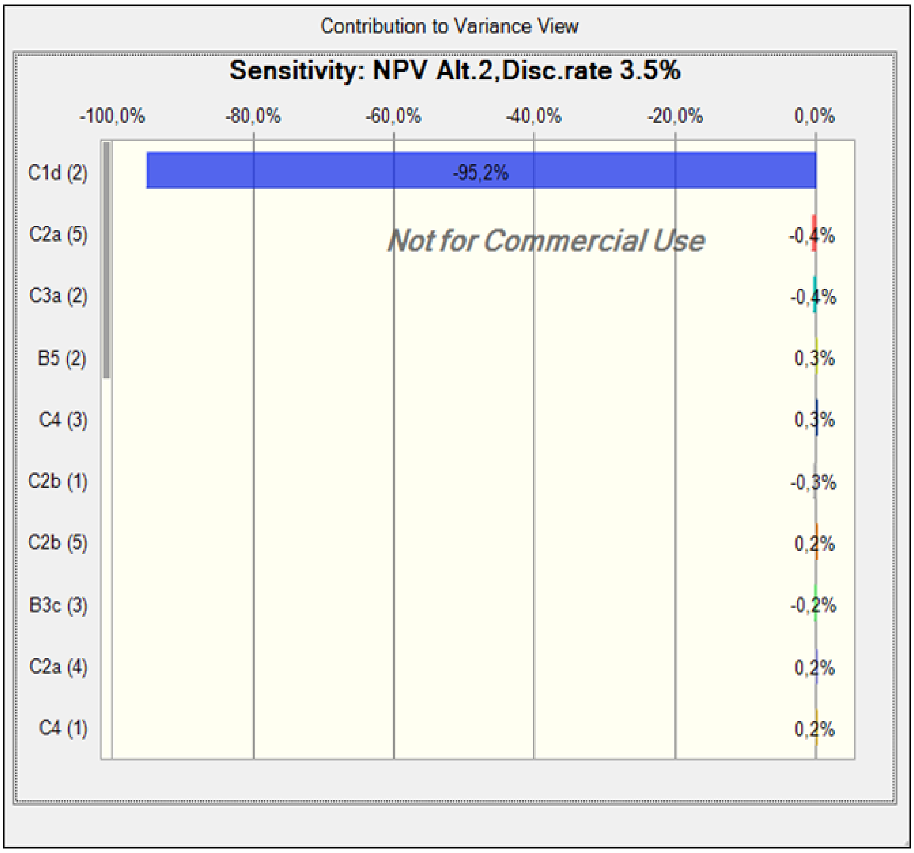

Figure J.2. Results of sensitivity analysis for Alternative 2. Discount rate is set to 3.5%.

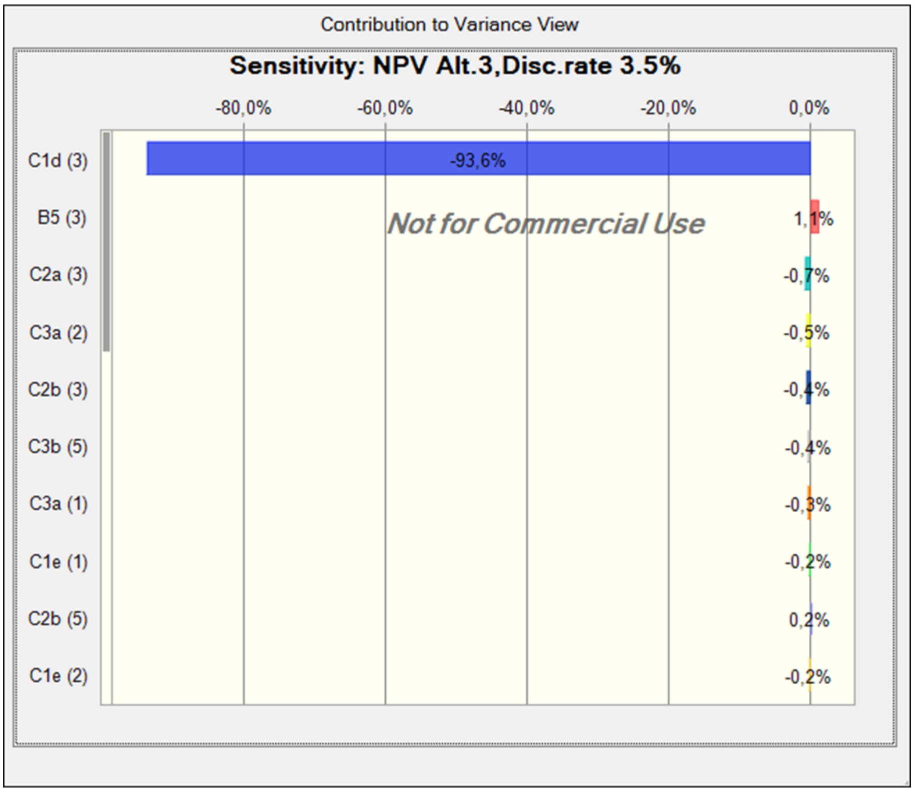

Figure J.3. Results of sensitivity analysis for Alternative 3. Discount rate is set to 3.5%.

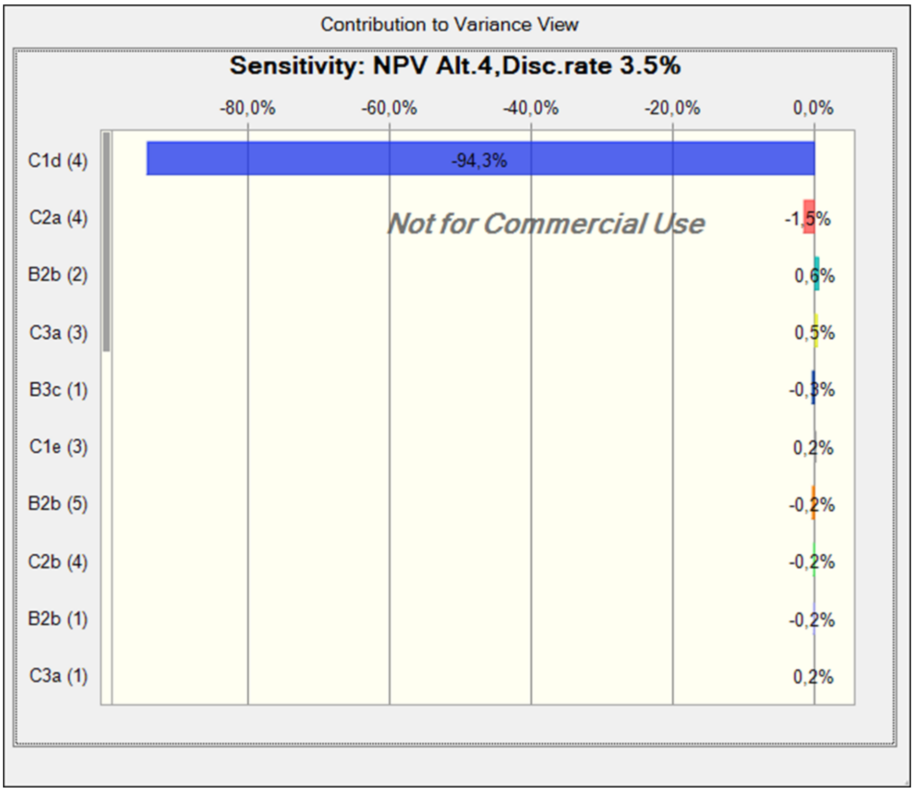

Figure J.4. Results of sensitivity analysis for Alternative 4. Discount rate is set to 3.5%.

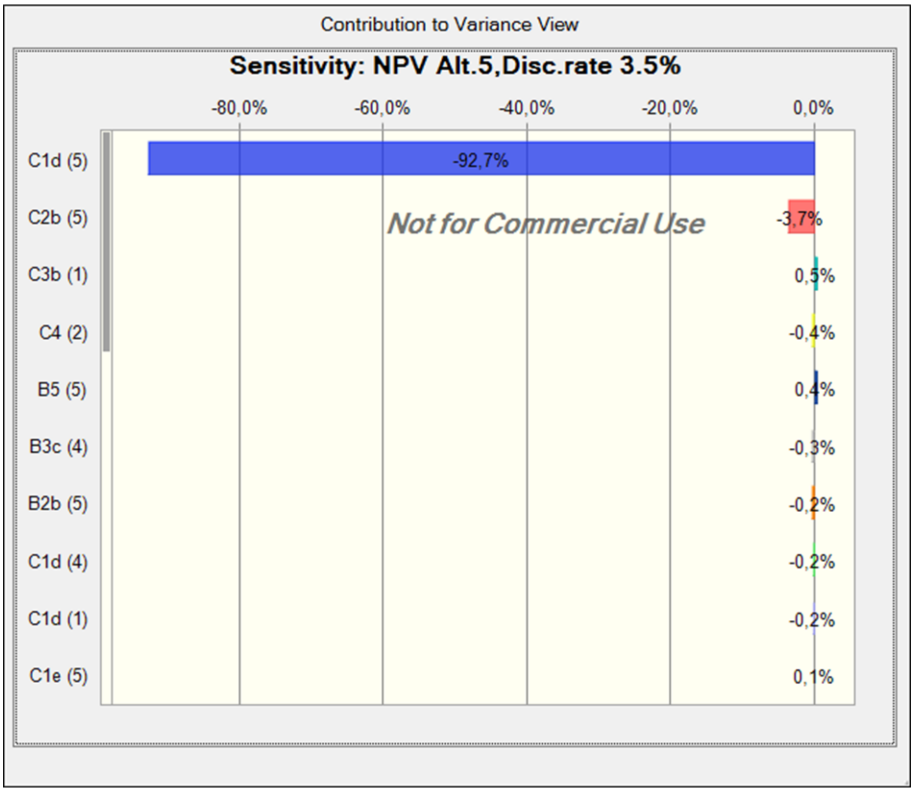

Figure J.5. Results of sensitivity analysis for Alternative 5. Discount rate is set to 3.5%.