HANDLING LARGE-SCALE HEAVY METAL CONTAMINATED SOIL AT NÄSUDDEN, SKELLEFTEÅ

A Life Cycle Assessment and Economic Analysis Study

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ABSTRACT

Industrialization has increased heavy metal contamination in soil through decades of aerial pollution. These heavy metals tend to spread through the soil and into freshwater sources due to their high mobility. Näsudden, located in Skellefteå is one of these sites, which have experienced historical air pollution from the Rönnskär industrial complex nearby. This has led to elevated levels of arsenic, copper, lead, and zinc far above the national hazardous waste reference limits in the organic top layer at the site. As preparations to construct a large-scale industrial compound at the site have commenced, this contaminated soil has to be excavated and remediated before any construction can take place. Through the usage of Life Cycle Assessment and an economic analysis based on the basics of Life Cycle Costing in collaboration with Skellefteå municipality, three different scenarios were investigated to determine which remediation solution would cause the lowest negative environmental, human health and economic impact. Scenario 1 consisted of landfilling the hazardous soil ex-situ, Scenario 2 consisted of encapsulating the hazardous soil inside a noise barrier without pre-treatment in-situ, and Scenario 3 combined mobile on-site soil washing with encapsulation inside the noise barrier in-situ. The result showed that the solution of encapsulating the hazardous soil without any pre-treatment in Scenario 2 would be the most beneficial and sustainable according to 9 out of 10 impact categories related to natural environment and resources, and human health. Thus, Scenario 2 was deemed as the most valid solution for the project. However, the scenario showed higher impact related to ecotoxicity in freshwater than Scenario 1 and Scenario 3 due to hazardous uncollected leachate from the noise barrier. The uncertainties related to the organic structure of the noise barrier combined with excluded environmental costs suggests that further investigation should be made in effectivizing the noise barrier before implementation.

Keywords: Heavy metal contaminated soil, Soil remediation, Näsudden, Life Cycle Assessment (LCA), Economic analysis, Sensitivity analysis, Data quality analysis, Uncertainty propagation, Environmental impact, Human health impact, Economic impact

PREFACE

This project is near and dear to my heart, as I grew up in the outskirts near the studied site of Näsudden, and have been keeping myself updated on the impacts of heavy metal soil contamination across and near Skelleftehamn, Ursviken and Bureå, which have affected its habitants negatively. This study was primarily made with these people in mind, and to assist and collaborate with Skellefteå municipality for sustainable development.

First, I would like to thank my supervisors at Skellefteå municipality: Johanni Wellenius and Olov Rydlinge for providing me with the site-specific materials needed to conduct the study, and for giving me the opportunity to do a study in a personal field of interest. I would also like to thank Mikael Lindmark at Skellefteå municipality for providing me with more detailed information regarding the structure of the project.

Thank you to my supervisor Harry Tibbetts who provided me with an updated version of the EASETECH software and database, as well as material, data, and information regarding the process of conducting a LCA focused study. Your support and expertise have played a key role behind the success of finalizing this study.

And thank you to my examinator Nathalie Kampmann at Mälardalen University for providing me with feedback regarding my report, further strengthening the end result.

And lastly, I would like to thank my family and friends, for their generous support throughout the study.

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SUMMARY

Soil contamination from heavy metal pollution is a rising concern globally with increasing populations worldwide and historical anthropogenic pollution further increasing its spread across the ground and into freshwater sources. As the global industrialization increases, so does the risks of constructing large-scale industrial complexes on areas with hazardous levels of heavy metals in the soil. In Sweden, remediating contaminated soil in a heavily affected site is oftentimes an obligation for the municipality to handle before any further construction can be made. Remediating these sites are often negatively impacting the environment both on a local scale, and a global scale, as the soil needs to be excavated and treated, either in-situ or ex-situ, resulting in the usage of heavy machinery and excessive amounts of hazardous soil transportation often driven on fossil fuel. Handling the hazardous soil may also negatively impact the health of the workers remediating the site, and as the human health risks remains unless treated correctly, the industrial personnel at the site may be exposed to toxic heavy metals post-construction.

Decades of aerial pollution from the Rönnskär industry outside Skellefteå has elevated levels of arsenic (As), copper (Cu), lead (Pb), and zinc (Zn) above hazardous reference limits in the topsoil at the nearby location of Näsudden, which would require approximately 100000 tonnes of contaminated fine fraction soil to be excavated and remediated. The traditional way of handling these types of large-scale contaminated soil in the country is through excavation and landfilling, where the contaminated soil waste gets deposited as hazardous waste indefinitely. This process is environmentally, socially in terms of human health, and economically unviable, as it would require a significant amount of transportation potentially increasing traffic emissions and risks of traffic accidents. Alternative remediation techniques effectivity and feasibility are heavily dependent on the properties of the soil and its contaminants, the scale and timeframe of the project, the costs of the project, and the climate where the project is to take place.

The purpose of the study is to provide Skellefteå Municipality with a sustainable and economically viable solution to mitigate the environmental impacts of handling and treating large-scales of contaminated soil, while mitigating health hazards to provide a safe working environment for both future industrial workers and the workers handling the contaminated soil. It is conducted to investigate, through the combination of a literature review, Life Cycle Assessment (LCA) and economic evaluation based on the basics of Life Cycle Costing (LCC) analysis, alternative remediation techniques are to model and evaluate and compare them. It evaluates three different solutions as scenarios, where the excavated hazardous fine fraction gets landfilled in Scenario 1, encapsulated without prior treatment inside a noise barrier in Scenario 2, and undergoes a more complex remediation combination of mobile soil washing and encapsulated post-treatment inside a noise barrier in Scenario 3.

These scenarios were modelled in the LCA software EASETECH and consisted of the stabilized reference flows from three different excavation points and the material generated from external soil being transported to the site to be used as noise barrier construction material, as well as the functional unit flow to treat 1 tonne of hazardous fine fraction to

immobilize its contaminants under critical levels, using primary in-situ specific data parameters and gathered secondary data parameters.

The results show, after a Life Cycle Impact Assessment (LCIA), contribution analysis, sensitivity analysis, data analysis, uncertainty propagation and discernibility analysis were conducted, that Scenario 2, where the hazardous fine fraction gets encapsulated without treatment is the most preferrable solution to remediating the soil to mitigate the negative impacts on the natural environment, its resources and the human health risks, while lowering the total costs. However, the risks of freshwater ecotoxicity from uncollected leachate from the noise barrier increases when the hazardous material gets reused without treatment.

The economic analysis results also showed that Scenario 2 were the most beneficial solution compared to Scenario 1 and Scenario 3. Scenario 1 would cost Skellefteå municipality approximately 2437.34 SEK/tonne to remediate the hazardous fine fraction soil, while Scenario 2 would cost them approximately 222.83 SEK/tone, and Scenario 3 an approximately 1169.65 SEK/tonne.

The high uncertainty from the leachate parameters for all heavy metals except Pb indicates that the variance in the impact categories related to human toxicity and freshwater ecotoxicity is higher across all scenarios, especially in Scenario 2 and Scenario 3 as the hazardous fine fraction leachate gets collected in Scenario 1. Although these leachate parameters were primary data collected from lab measurements made of the soil from the site with low Data Quality Ratings (DQR), they were based on an average of heavily fluctuated lab results, increasing the uncertainty as standard deviations.

To limit the environmental, human health and economic impacts of remediating a large volume of soil contaminated with As, Cu, Pb and Zn at hazardous levels with a time frame of 1-2 years, Skellefteå municipality should encapsulate the soil inside the noise barrier without pre-treatment, instead of landfilling it or washing it in-situ beforehand. If the solution is brought into practice, further research should be made in effectivizing said noise barrier further, either by including a leachate collection system or utilizing a remediation technique that could be performed without a limited time frame.

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NOMENCLATURE

Symbol	Description	Unit
$\bar{x}$	Sample Mean	[Parameter dependant]
d	Distance	km
$HHV_{inverted}$	Inverted Higher Heating Value	L/MJ
m	Mass weight	kg
M	Molarity	mol/L
n	Number of variables	[Parameter dependant]
P	Cost	SEK
s	Sample standard deviation	[Parameter dependant]
t	Time	h
V	Volume	m^3
ρ	Density	mg/ m^3

ABBREVIATIONS

Abbreviation	Description
Al	Aluminium
As	Arsenic
C	Completeness
CAH	Chlorinated aliphatic hydrocarbons
Cd	Cadmium
CDW	Construction Demolition Waste
CO_2	Carbon Dioxide
$CO_{2\text{-Eq}}$	Carbon Dioxide Equivalent
CTUe	Comparative Toxic Unit for Ecosystems
CTUh	Comparative Toxic Unit for Humans
Cu	Copper
DQR	Data Quality Rating
EASETECH	Environmental Assessment System for Environmental Technologies
EU	European Union
FA	Farligt Avfall (Hazardous Waste)
Fe	Iron
FU	Functional Unit
GR	Geographical Representativeness
GWP	Global Warming Potential
H_2SO_4	Sulfuric Acid
H_3PO_4	Phosphoric Acid
Hg	Mercury
HP	Hazardous Properties
ILCD	International Reference Life Cycle Data System
IPCC	Intergovernmental Panel on Climate Change
kg	Kilograms
km	Kilometres
L/S	Liquid-to-Solid
LCA	Life Cycle Assessment
LCC	Life Cycle Costing
LCI	Life Cycle Inventory
LCIA	Life Cycle Impact Assessment
M	Molarity

Abbreviation	Description
mg	Milligrams
MKM	Mindre Känslig Markanvändning (Less Sensitive Land Use)
Mn	Manganese
NaOH	Sodium Hydroxide
ND	Normal Distribution
P	Reliability (Precision Uncertainty)
PA	Perturbation Analysis
PAH	Polycyclic Aromatic Hydrocarbons
Pb	Lead
PM	Particulate Matter
S	Sulphur
S/L	Solid-to-Liquid
S1	Scenario 1
S2	Scenario 2
S3	Scenario 3
SA	Sensitivity analysis
SDG	Sustainable Development Goal
SEK	Swedish Krona
SGI	Statens Geotekniska Institut (Swedish Geotechnical Institute)
SGU	Sveriges Geologiska Undersökning (The Geological Survey of Sweden)
SR	Sensitivity Ratio
Swedish EPA	Swedish Environmental Protection Agency
TeR	Technological Representativeness
TiR	Time-Related Representativeness
TOC	Total Organic Carbon
TS	Total Solids
WWTP	Wastewater Treatment Plant
XRF	X-Ray Fluorescence
Zn	Zinc

DEFINITIONS

Definition	Description
FA (Farligt Avfall) (Hazardous Waste)	Recommended concentration limits for classification of contaminated masses as hazardous waste based on the 15 hazardous properties (HP1-HP15) from the European Union (EU) Commission Regulations No 1357/2014 and 2017/997 (Elert et al., 2019, pp. 38–39, 2019, pp. 7–8).
MKM (Mindre Känslig Markanvändning) (Less Sensitive Land Use)	Reference value for risk assessment of soil contamination for less sensitive development areas (Naturvårdsverket, 2025c).
Noise Barrier	Barrier construction for encapsulating the hazardous fine fraction soil waste in-situ.
pH	Used to determine if a solution or soil is basic or acidic on a scale of 0-14. Low pH indicates acidic and a high pH indicates basic (United States Environmental Protection Agency, 2026).
Scenario 1: Landfilling	Base scenario where the excavated heavy metal contaminated fine fraction gets transported ex-situ for landfilling.
Scenario 2: Noise barrier encapsulation	Proposed scenario where the excavated heavy metal contaminated fine fraction gets encapsulated inside an in-situ noise barrier without pre-treatment.
Scenario 3: Soil wash and Noise barrier encapsulation	Alternative scenario where the excavated heavy metal contaminated fine fraction gets washed in mobile on-site soil washing station before it gets encapsulated inside an in-situ noise barrier.

1 INTRODUCTION

For a soil to be considered contaminated, its organic or inorganic contaminant levels must surpass their natural levels. These levels are oftentimes elevated due to rising populations and historical pollution from industrialization. This contamination is a concern that affects the environment and human health negatively (Bini, 2010, pp. 1–5; Fernández Rodríguez et al., 2014, p. 344), and due to the risk of further toxic spread from long lasting and accumulating heavy metals (Wieczorek et al., 2020, pp. 1–2), it is of importance to mitigate the contamination as soon as possible.

In order to treat the contaminated soil, the choice of method depends on the structure of the soil, availability of remediation techniques, sustainability and economic feasibility of the method (Fernández Rodríguez et al., 2014, p. 344), and the complex nature of metals (Wieczorek et al., 2020, p. 2) can potentially make any decision-making harder to finalize.

1.1 Background

The Skellefteå municipality are planning on expanding its industrial establishments on Näsudden, located in Skelleftehamn, outside of Skellefteå. To build this establishment, the Skellefteå municipality has to excavate the top soil layer to remediate the contaminated soil which has been exposed to historical airborne pollution from a nearby located industrial compound (Tyréns AB & Skellefteå Kommun, 2017, p. 5). This historical airborne pollution of arsenic (As), cadmium (Cd), copper (Cu), lead (Pb), zinc (Zn) and sulphur (S) has occurred since the 1930s (Pihl Karlsson & Nerentorp, 2023, pp. 5–8; Sweco, 2025b, p. 5), and has since then rapidly increased the levels of primarily As, Cu, Pb and Zn in the soil at the area (Tyréns AB & Skellefteå Kommun, 2017, p. 14). Since the 1970s, mitigation strategies have been implemented to limit future pollution from the industrial compound (Sweco, 2025b, p. 5), but due to the physiochemical properties of the heavy metals and the physical and chemical properties of the soil, the contaminants have spread and the levels have reached critical levels in regards to Avfall Sveriges Farligt Avfall (Hazardous Waste) (FA) recommended levels based on the European Union commission regulations No 1357/2014 and 2017/997 (Elert et al., 2019, pp. 38–39, 2019, pp. 7–8) throughout the years, mostly occurring at depths of 0-0.1 meters at the area (Afry, 2022; Dube et al., 2000, p. 2; Geisler, 2025, pp. 7–8). At deeper depths, the heavy metal levels diminishes, except for As which tends to leach and spread deeper into the soil structure (Afry, 2022; J. Wellenius & O. Rydlinge, personal communication, March 24, 2026).

At this depth, the highest levels of the contaminants occur in the fine fraction of the top organic layer, where maximum levels have been measured of As, Cu, Pb and Zn of 2900 mg/kg, 9500 mg/kg, 16000 mg/kg and 5600 mg/kg (Afry, 2022; Geisler, 2025, p. 13). In comparison, the regional maximum natural soil geochemical baseline background levels for soil in a radius of 10 km from the site, according to The Geological Survey of Sweden (SGU) consists of As, Cu, Pb and Zn levels of 13.1 mg/kg, 22.3 mg/kg, 12.8 mg/kg and 14.5 mg/kg. However, these background levels can fluctuate between the measure points and may exclude certain measure points in the radius (Sveriges Geologiska Undersökning, n.d., p. Bilaga 1; Vendt & Paulsson, 2025, pp. 11–12).

In its plan to expand and renew Näsudden, the municipality, Skellefteå Kraft and SkyNRG plan to build an industrial compound consisting of a manufacturing plant for renewable aviation fuel and structures relevant for operating and running the plant at Näsudden (SkyKraft, n.d.; Sweco, 2025b, pp. 5–6). As the heavy metal pollution in the top soil is posing a threat to the environment and human health of those working at the area, it must be handled and removed before any construction can be started (Bjuhr & Andreas, 2023, p. 5; Sweco, 2025b, p. 5; Tyréns AB & Skellefteå Kommun, 2017, p. 14; J. Wellenius, personal communication, February 2, 2026)

Treating this highly contaminated fine fraction soil requires a large area of topsoil excavation, which will result in large amounts of soil waste that needs to be sustainably remediated. There are currently two different strategies proposed for handling this excess contaminated soil to ensure limited risks of health and environmental impacts on a short- and long term industrial operation (Bjuhr & Andreas, 2023, p. 8). The first strategy, Scenario 1, is the traditional way of handling said waste in Sweden, where the soil gets excavated and landfilled (Papageorgiou et al., 2021, p. 2; J. Wellenius, personal communication, February 2, 2026).

This requires the municipality to transport the excavated hazardous soil waste for landfill disposal at Dåva waste handling facility in the nearby city of Umeå, approximately 120 km from the site. This would result in approximately 3300 truckloads of soil waste needed for transportation (Geisler, 2025, p. 24; J. Wellenius, personal communication, November 27, 2025) and soil replacement transported to Näsudden, resulting in high environmental impacts and costs (Bjuhr & Andreas, 2023, p. 5; Sweco, 2025b, p. 10). The coarse fraction of the soil waste would then be reused on-site. Even though this traditional way of remediating large amounts of contaminated soil comes with its disadvantages, it is still a widely used method for similar case projects as it is considered a simple and reliable method of remediating contaminated soil waste when other techniques are limited (Geisler, 2025, p. 27).

The second strategy, Scenario 2, which Skellefteå municipality is proposing in permit application to the Land and Environment Court for handling and remediating the contaminated soil, is to use a containment and barrier process, where the hazardous fine fraction, will be encapsulated inside a noise barrier without pre-treatment located at the border of the industrial compound to limit its noise pollution and negating the amount of soil needed to be discarded. An answer to the proposal is expected due to February 2027, to whether the solution is approved and what levels of heavy metal contamination is accepted for encapsulation. Any fine fraction consisting of heavy metal levels above these conditioned limits will have to be discarded (Bjuhr & Andreas, 2023, p. 5; J. Wellenius & O. Rydlinge, personal communication, March 24, 2026). This solution is however demanding on proper logistics to function correctly and comes with risks of handling and structuring with the waste material, as workers would need to handle high amounts of hazardous soil (Bjuhr & Andreas, 2023, p. 39). As testing on this solution only has been made on a pilot scale, other uncertainties regarding the feasibility and sustainability remains (Geisler, 2025, p. 40), as the long-term effects of precipitation might increase the leachability of the heavy metals from the noise barrier (Vendt & Paulsson, 2025, pp. 22–27).

Due to the uncertainties of these solutions, and to align with the city's sustainability goals, the municipality wishes to find a solution to remediate the large amounts of contaminated soil waste with lower environmental and economic impacts, whilst limiting the negative impacts of said noise barrier (J. Wellenius, personal communication, November 27, 2025, personal communication, February 2, 2026).

In summary, Skellefteå municipality have to find a solution to remediate 100000 tonnes of contaminated fine fraction soil at Näsudden, that has through decades of industrial airborne pollution experienced elevated levels of As, Cu, Pb and Zn above their respective national hazardous waste reference limits, in order to limit the environmental and health risks connected to constructing an industrial compound at the area (Geisler, 2025, p. 22; Pihl Karlsson & Nerentorp, 2023, pp. 5–8; Tyréns AB & Skellefteå Kommun, 2017, p. 5). The proposed solutions of landfilling and encapsulating the contaminated fine fraction inside a noise barrier may lead to increased environmental impacts from increased leaching and excessive waste transportations. To evaluate these options, as well as comparing them to other alternative remediation techniques, and to provide Skellefteå municipality with a solution that is both sustainable and beneficial, a combination of literature review-research, Life Cycle Assessment (LCA) and an economic analysis based on the basics of Life Cycle Costing (LCC) is used. This combination provides an increased knowledge of alternative pathways, and as the functional unit (FU) stays the same throughout the LCA and economic analysis, the proposed scenarios, Scenario 1 and Scenario 2 can be compared to the alternative scenario, Scenario 3 (Ding et al., 2024, p. 12; Yang et al., 2025, p. 4).

1.2 Purpose/Aim

The purpose of this case study is to investigate the environmental, human health, and economic impacts related to handling and remediating heavy metal contaminated soil waste in Skellefteå. As the industry compound at the location will require a large amount of land, the soil waste generated from topsoil removal would require high amounts of waste transportation and disposal using a traditional method of excavation and landfill.

By researching other types of soil remediation techniques, and by using a LCA and economic analysis based on LCC analysis, the difference in environmental, human health and economic impacts between Scenario 1 of landfilling, Scenario 2 of encapsulation inside noise barrier, and other types of remediation techniques could potentially open to a more beneficial solution while mitigating the environmental and health impacts of the process. The third scenario, Scenario 3 consisting of encapsulation inside noise barrier after on-site mobile soil washing, were chosen as a viable option to compare with the other two proposed scenarios.

The results from the study could work as a guideline for Skellefteå municipality and aims to provide them and potentially other municipalities in similar situations with alternative solutions to handling excess amounts of metal and inorganic contaminated soil.

1.3 Research questions

To determine possible solutions to enhance the environmental, human health and economical sustainability of handling and remediating the heavy metal contaminated soil, this study will try to research and gather answers regarding:

- What are the major concerns with the proposed base techniques, and can they be mitigated?
- Which alternative remediation techniques are viable considering the volume, time limitation and heterogeneity of the soil?

And lastly, to determine the viability between the alternative soil handling and remediation methods, a main research question needs to be answered:

- What are the differences in environmental, human health and economic impacts, investigated using LCA and economic analysis, between the proposed solutions of handling and remediating the soil after a large-scale excavation?

1.4 Delimitation

The study is delimited to only using the most recently measured data available for each contaminant. As the aim of the study is to provide an alternative solution which could be implemented based on today's standard, a goal to not use any historical data from pre-2010 were implemented.

As previous research has been made on the potential of utilizing the heavy metal contaminated soil by solidifying it with concrete in order to use the product as building material at the site without success (J. Wellenius, personal communication, November 27, 2025), this particular solution, as well as other stabilization/solidification techniques requiring mixing the soil with a construction material will not be included in further investigation, and other alternatives will be researched instead.

As mentioned by Skellefteå municipality, the time limitations of the project are important (J. Wellenius, personal communication, November 27, 2025). Thus, alternatives for soil remediation that requires longer time rates than two years will not be considered or included in the LCA and economic analysis, yet they have been included in the literature review.

Based on in-situ measurements done by Tyréns AB & Skellefteå Kommun (2017, pp. 1–33), the contaminants measured in the soil are arsenic (As), barium (Ba), lead (Pb), cadmium (Cd), carbon monoxide (CO), copper (Cu), chromium (Cr), mercury (Hg), nickel (Ni), vanadium (V), and zinc (Zn), yet the contaminants above critical Hazardous Waste (FA) limits: As, Cu, Pb and Zn, have only been considered and modelled in the LCA.

Alternative remediation techniques that do not effectively remove these contaminants over a set time-period of 2 years, including Thermal remediation, Phytoremediation, Biochar remediation, Stabilization/solidification and Soil flushing have not been included in the LCA and economic analysis, yet they have been included in the literature review.

An attributional approach has been made for the LCA and economic analysis, as some processes will be considered the same for any type of scenario, such as excavation, soil separation and rock hill blasting, with the same system boundaries and functional unit. These scenarios are modelled as they are predicted to be. This approach is based on the municipality's best interest to determine the change of environmental, human health and economic impacts between different solutions.

Only the washing agents heavy metal removal efficiency and cleaned soil to hazardous waste material ratio have been included in modelling the soil washing process for Scenario 3, thus excluding any impacts caused by production or usage of said washing agents.

The results from the study are only to be used as an indication for possible treatment methods of heavy metal contaminated soil waste. Further research is advised to be made regarding different viable pathways at a pilot scale before any implementation or investment is to be made.

2 LITERATURE REVIEW

To understand and determine a solid alternative for handling and remediating the heavy metal contaminated soil waste, a deeper understanding of the environmental impacts of contaminated soil and soil remediation techniques methods were studied.

Handling and treating contaminated soil waste are often made using different technologies for differing contaminant content within the soil. It can either be done in-situ, or ex-situ using techniques such as excavating and landfilling, and remediation techniques such as bioremediation, soil washing, chemical oxidation, thermal treatment, vapor extraction, incineration, physical treatment or other alternative methods (EPA, 1997, p. 2, 2025; Papageorgiou et al., 2021, p. 2).

This chapter dives into different commonly used remediation methods, to determine viable methods for remediating large scales of heavy metal contaminated soil at a location located in the Northern hemisphere, as well as weighing them against the sustainability targets of Skellefteå municipality and determining gaps in currently available and previously conducted similar case studies. This builds a foundation for the Goal and Scope in preparation for the LCI and LCIA to be conducted (European Commission, 2010, p. 11).

2.1 Site properties

The top layer of the soil at Näsudden consists of moraine, with minor parts of swell-sediment, sediment blocks, lightweight concrete, stones, industrial slag products, gravel and peat. There are also smaller rock mountains and cliffs occurring at the area (Geisler, 2025, p. 8; Sweco, 2025b, pp. 8–9) as shown in Figure 1.

Figure 1: Photograph of rock mountains which needs to be blasted and excavated.

The soil conditions, rock mountains, and their respective locations at the area are shown in Figure 2.

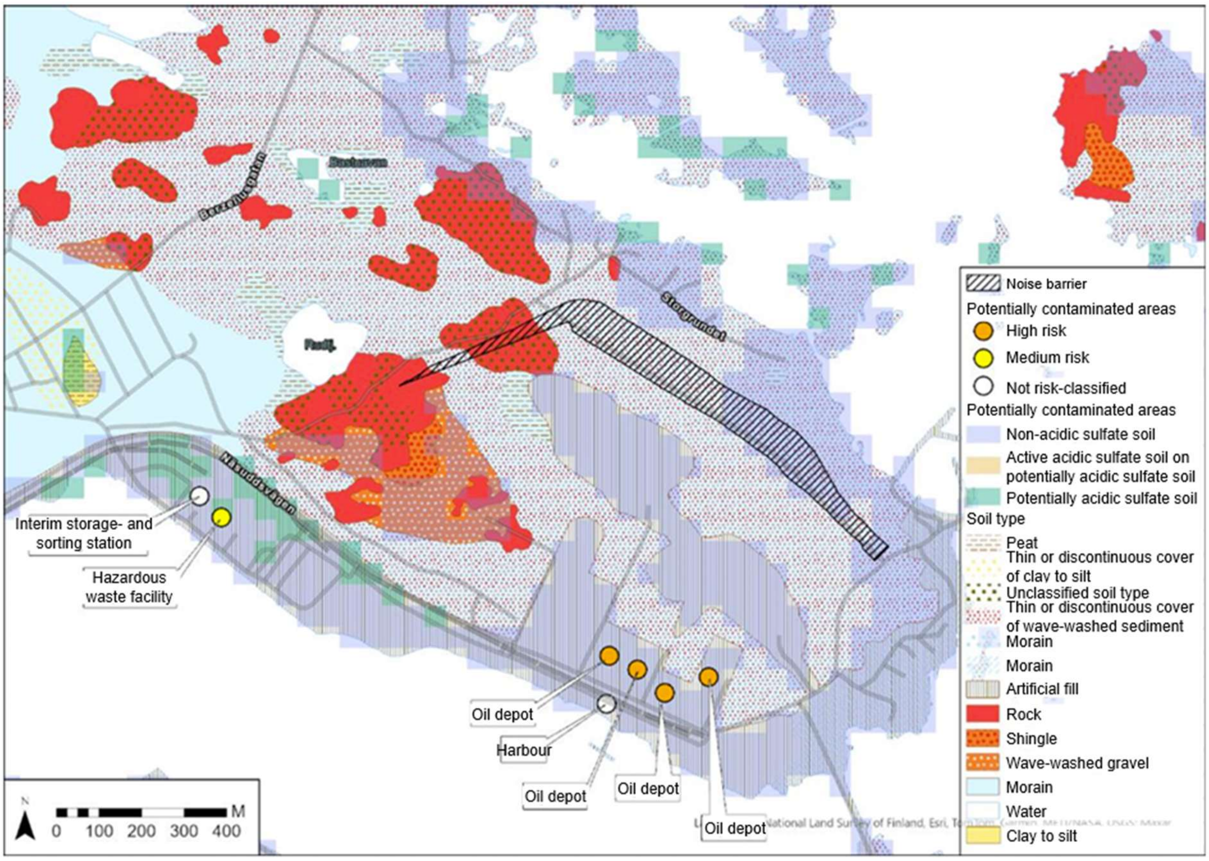

Figure 2: Map showcasing the soil conditions at the proposed Näsudden industrial compound (Sveriges Geologiska Undersökning, 2014, pp. 1–12; Sweco, 2025a, p. 14).

The excavation processes are divided into the topsoil excavation of a depth of 0.4m, blasting and excavation of rock hills, and excavation of landfills located to the north and south of the area, as well as outside the landfills and above hills. The planned amount of excavation sites and its respective volume divided into excavated materials is shown in Table 1.

Table 1: Planned amount of excavated material volume from the different excavation sites (Geisler, 2025, p. 20).

Excavation process	Total volume (m^3)	Material (%)	Material volume (m^3)
Excavation 0.4 m depth	2.70E+05	20% fine fraction	5.40E+04
		80% coarse fraction	2.16E+05
Excavation, northern landfill (down to terrace)	2.90E+05	85% siporex	2.47E+05
		5% moraine	1.45E+04
		5% sewage sludge	1.45E+04
		5% peat	1.45E+04
Excavation, southern landfill (down to terrace)	1.75E+05	20% siporex	3.50E+04
		70% moraine	1.23E+05
		10% peat	1.75E+04
Excavation, northern landfill (from terrace to moraine)	2.00E+04	85% siporex	1.70E+04
		5% moraine	1.00E+03
		5% sewage sludge	1.00E+03
		5% peat	1.00E+03
Excavation, southern landfill (from terrace to moraine)	1.10E+05	20% siporex	2.20E+04
		70% moraine	7.70E+04
		10% peat	1.10E+04
Excavation, peat, outside landfills	1.50E+04	100% peat	1.50E+04
Excavation above hills	4.75E+05	100% moraine	4.75E+05
Rock excavation/blasting	1.14E+06	100% rock	1.14E+06

The heterogeneous soil contains a mixture of heterogeneous contaminants, and due to this heterogeneity (Geisler, 2025, pp. 9–12), the treatment method must be able to reduce the elevated levels of As, Cu, Pb and Zn under safe levels without imposing a risk of contamination spreading in the soil, groundwater or freshwater sources within the area (Geisler, 2025, p. 13; J. Wellenius, personal communication, February 2, 2026). The area of the affected top soil that needs to be treated are approximately 839 000 m^2 (Sweco, 2025b, p. 28) with a total depth consisting of organic and mineral soil of 0.4 m (Bjuhr & Andreas, 2023, p. 10; Sweco, 2025b, p. 41). Excavation of this depth has been proven, at the site, to limit the contaminants below their respective Farligt Avfall (Hazardous Waste) (FA) and Mindre Känslig Markanvändning (Less Sensitive Land Use) (MKM) reference values (Geisler, 2025, pp. 15–16). This amounted to an approximated capacity of 335 600 m^3 in volume of soil needed to be treated, resulting in approximate amounts of soil and contaminants in tonnes needed to be treated shown in Table 2.

Table 2: Approximated amount of soil capacity per tonnes needed to be treated at Näsudden.

Fraction	Capacity (tonnes)	Reference
Fine fraction soil	100 000	(Geisler, 2025, pp. 22–28)
As	35-46	(Sweco, 2025b, p. 5; Vendt & Paulsson, 2025, p. 5)
Cu	51-63	(Sweco, 2025b, p. 14)
Hg	0.1-0.5	(Sweco, 2025b, p. 5; Vendt & Paulsson, 2025, p. 5)
Pb	82-90	(Sweco, 2025b, p. 5; Vendt & Paulsson, 2025, p. 5)
Zn	30-42	(Sweco, 2025b, p. 15)

This capacity and volume is considered a large amount compared to smaller scale treatment operations (Helldén et al., 2006, p. 13), which increases the complexity of capable treatment solutions. However, critical levels of As, Cu, Pb and Zn above the Swedish Environmental Protection Agency (Swedish EPA) FA reference values have only been measured at the top organic layer (0-0.1 m) at the site, meaning this layer needs to be treated in order to mitigate the risks (Geisler, 2025, pp. 13–14; Skellefteå Kommun, 2022a; Tyréns AB & Skellefteå Kommun, 2017, pp. 22-27 Bilaga 4) as the vast majority of elevated contaminants exist in the fine fraction soil (Geisler, 2025, p. 28). Points where the measurements of these elevated levels in the top layer of the soil (Geisler, 2025, pp. 12–13) is shown in Figure 3.

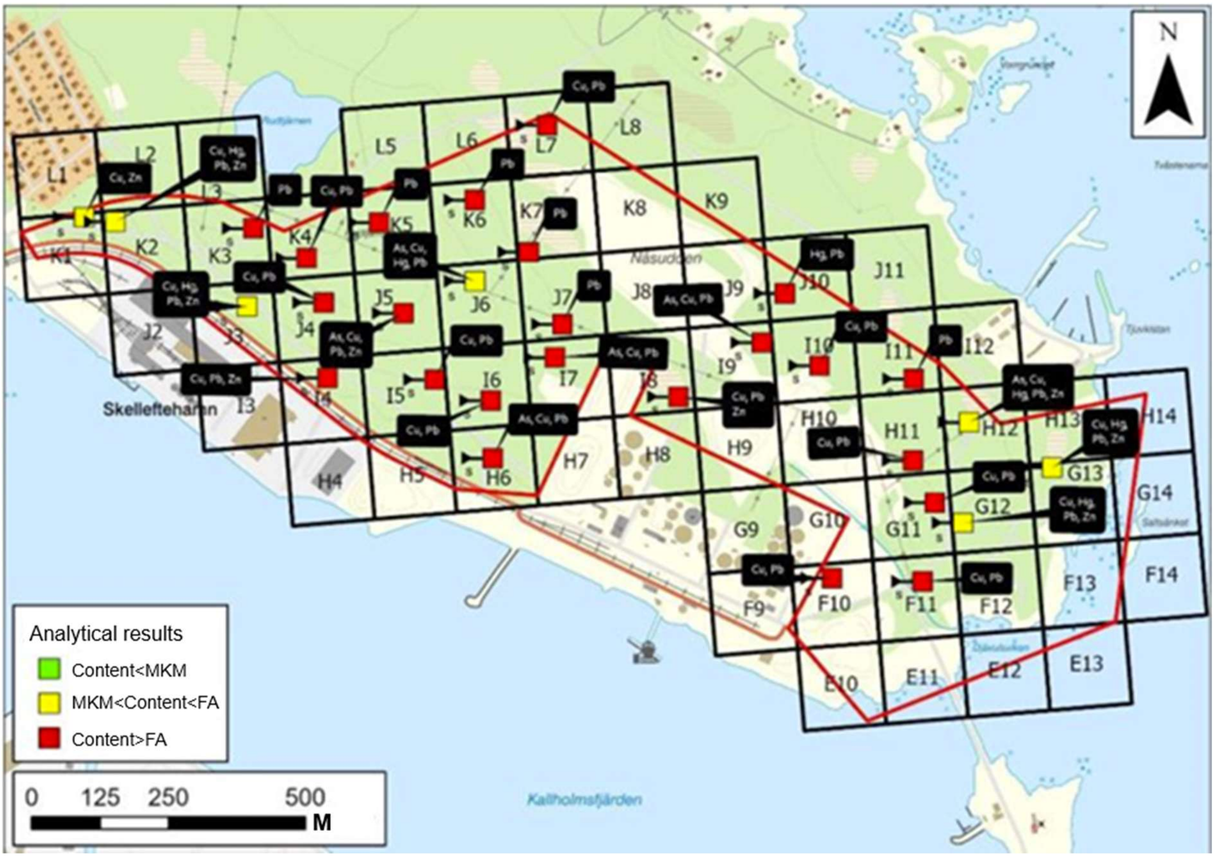

Figure 3: *Map showcasing measure points of critical contaminant levels above the Swedish EPA FA reference values in red, and the Swedish EPA MKM reference values in yellow, measured using XRF (Geisler, 2025, p. 13).*

The time frame for the treatment also plays a key role in choosing valid remediation techniques as Skellefteå municipality had mentioned that the industrial construction were planned to begin next year, 2027 (J. Wellenius & O. Rydlinge, personal communication, March 2, 2026).

However, as finding a remediation solution which fits all criterias to a full extent would limit the possible outcomes of alternatives suitable for an LCA and economic analysis. Thus, an assumption were made, to align with previous studies connected to Näsudden conducted by Thyréns, Afry and Sweco to mainly focus on the heterogeneity of contaminants, and mitigating further spreading of contaminants (Bjuhr & Andreas, 2023, p. 8; Tyréns AB & Skellefteå Kommun, 2017, p. 12; Vendt & Paulsson, 2025, p. 8) over an appropriate time period.

2.2 Soil contamination

Heavy metals can be found naturally in soils and sediments worldwide but has throughout the years seen an increase from anthropogenic sources, particularly the industrial sector (Dube et al., 2000, p. 1; Michael, 2023, pp. 1–2; Sethi & Gupta, 2021, p. 4). This type of pollution can be toxic in lower amounts, yet elevated levels pose an even larger threat to the ecosystem and the health of all living beings (Sethi & Gupta, 2021, pp. 1–2).

The top soil fine fraction layer at Näsudden measured at a depth of 0-0.1 m consists of As, Cd, Cu, Pb, V and Zn levels above the Swedish EPA reference value for risk assessment of soil contamination for less sensitive development areas, called Less Sensitive Land Use, or Mindre Känslig Markanvändning (MKM) in Swedish, and As, Cu, Pb and Zn above the Avfall Sverige hazardous waste reference values called Farligt Avfall (Hazardous Waste) (FA) (Naturvårdsverket, 2025b, 2025c; Sweco, 2025a, pp. 14–20; Tyréns AB & Skellefteå Kommun, 2017, pp. 22-27 Bilaga 4). The MKM reference value are based on the environmental and health risks of contaminated soil in less sensitive land, such as soil at industrial sites, and is measured based on impacts on human health, soil environment, ground- and surface water (Naturvårdsverket, 2009, p. 23) while the FA reference value is a limit where waste with contaminant levels above it are classified as hazardous and should be treated as such based on the European Union Commission Regulations No 1357/2014 and 2017/997 15 hazardous properties (HP1-HP15) regarding Explosive-, Oxidizing-, Flammable-, Irritating-, Specific organ toxic-, Acute toxic-, Carcinogenic-, Corrosive-, Contagious-, Reproductive toxic-, Mutagenic-, Gaseous-, Allergenic-, Ecotoxic-, and Hazardous property that is not directly exhibited by the original waste-classified waste (Elert et al., 2019, pp. 38–39, 2019, pp. 7–8).

2.2.1 Environmental impacts

Anthropogenic sources as the industrial sector have through decades of pollution elevated the heavy metal content of soil far above its natural limits. Aerial pollution from the Rönnskär copper and iron smelter have slowly led to increased heavy metal contents in the soil through precipitation, where they continue to spread within the soil and into freshwater sources further damaging the terrestrial and marine ecosystem (Ahmad et al., 2024, pp. 390–393; Geisler, 2025, pp. 7–8).

The Näsudden soil structure consists of highly mobile heavy metals, mainly As, Cu, Pb and Zn, at hazardous levels which spread through binding and sorption, either chemically, physically or biologically, to the environment where they remain for decades. The spreading of As, Cu, Pb and Zn is estimated to be approximately 12 kg/year, 1 kg/year, 3 kg/year and 4 kg/year respectively and depends on variables such as soil pH, redox potential, heavy metal leachability rate, the heavy metals ability to bind to the soil particles or structure, and the weather conditions of the area (Dube et al., 2000, pp. 1–2; Sethi & Gupta, 2021, p. 6; Svenska Geotekniska Föreningen, 2023b; Sweco, 2025b, p. 17; Vendt & Paulsson, 2025, p. 19).

At the site, elevated levels of Cu, Pb, and Zn have only been measured in the top layer and seem to taper off, whereas toxic levels of As have been found at deeper parts of the site. This is caused by the fact that Cu, Pb and Zn binds stronger to the organic top layer, while the As spreads down into the deeper parts of the soil (Afry, 2022; Geisler, 2025, pp. 7–8) with a higher mobility from increased pH-values and low redox potentials, especially into groundwaters with pH values around 6.5-8.5 (Svenska Geotekniska Föreningen, 2023b; Sweco, 2025a, p. 17). High levels of As in the soil disrupts the ecosystem and limits plant growth (Svenska Geotekniska Föreningen, 2023b), and in groundwater sources it may pollute potential drinking water (Vendt & Paulsson, 2025, p. 9).

The other heavy metals Cu, Pb, and Zn, binds with humic compounds, iron (Fe)-, aluminium (Al)-, manganese (Mn)-oxides, proteins or enzymes and can be toxic to the ecosystem in elevated levels, disrupting plant growth, and the soil biota where it may affect the nitrogen mineralization. Pb and Zn pose a higher risk of toxicity to animals from ingesting the contaminated plants, and water living organisms are especially at risk from Zn toxicity as they are affected at lower levels. Zn also has a higher mobility than Cu and Pb, and its solubility is increased in conditions of lower pH and oxidizing redox states. Cu is not as dependant on pH as As and Zn, as it may bind to organic material at both higher and lower levels of pH (Milton et al., 2018, pp. 1–6; Svenska Geotekniska Föreningen, 2023c, 2023d; Sweco, 2025b, pp. 18–19).

2.2.2 Human impacts

The health risks connected to the Näsudden site are those associated with inhalation of dusts and steam, skin exposure, and ingestion of contaminated soil and plants grown at- or around the area (Vendt & Paulsson, 2025, p. 9). The large excavation and remediation project, as well as the construction of the industry complex may have negative impact on the workers, and the nearby residents of the site, where the impacts of exposure depends on the amount, and time period of exposure (Sethi & Gupta, 2021, pp. 2–3). It is thus important that the levels of heavy metals are limited under critical levels before any construction can be started to limit the risks of human exposure.

The health risk are increased for the personnel working with the soil remediation and construction of the noise barrier, as they may be more likely to be exposed to the hazardous dust particles, soil, and sharp objects contaminated by the soil (Svenska Geotekniska Föreningen, 2022, pp. 55–56). To limit the risk, all machinery used for excavating and moving the hazardous soil must be properly cleaned after usage. The same precautions have to be made when moving the soil in-situ to limit the risk of further exposure (Svenska Geotekniska Föreningen, 2022, pp. 49–50). Transporting the soil ex-situ can also be problematic, as a high amount of truck transportations needed for a large-scale remediation project could increase the risks of road traffic accidents. Trucks colliding with other vehicles can have fatal consequences, as they are oftentimes larger, accelerate slower, and break slower than other vehicles (Vierth et al., 2008, pp. 41–42).

The combination of hazardous levels of heavy metals at the site plays a key role in the toxicity exposure, as the As in the soil greatly exceeds the levels for acute toxicity at 100 mg/kg (Naturvårdsverket, 2025a, p. 1). As is a cancerogenous heavy metal, which by exposure can lead to health issues such as skin, lung, liver and kidney cancer. Long-time exposure can also lead to damaged immune systems, lungs, liver and cardiovascular diseases. Due to its high toxicity, short-term exposure can lead to side effects such as vomiting and severe stomach aches (Karolinska Institutet, 2026b; Sweco, 2025b, p. 17).

Pb is also a highly problematic heavy metal, as it is highly toxic to humans. Pb poisoning can have catastrophic effects, as it can affect all organs of the person, and gets absorbed in the body quickly. Small doses may cause damage to the nervous system in adults, and may be transferred to the foster during pregnancy, or cause miscarriage. Long-term exposure to the heavy metal can cause cardiovascular diseases, damage to the blood cells and be fatal at higher levels (Karolinska Institutet, 2026a; Wani et al., 2015, pp. 55–57).

Cu and Zn are less toxic to humans, and naturally consumed with food, with health guideline values for long-time exposure at 96000 mg/kg and 160000 mg/kg respectively (Naturvårdsverket, 2025a, p. 1). However. short-term exposure to high levels of Cu could cause stomach aches and vomiting, and long-term exposure could cause permanent liver damage (Livsmedelsverket, 2026). There is also an increased risk of Zn poisoning from inhaling the Zn contaminated soil at the site, which could lead to stomach aches, vomiting, diarrhoea, or in rare cases neurological damage (Schoofs et al., 2024, pp. 4–7).

Another impact to keep in mind is the citizens of Skellefteå approval to investments in the remediation and treatment processes. As it is a municipal matter, some parts of the costs might indirectly fall on the inhabitants as taxpayers, it may thus be for the best interest of the municipality to keep the investment costs as low as possible, while still promoting a sustainable solution.

2.3 Soil remediation

Soil remediation techniques can be done in three different ways: Ex-situ, On-site and In-situ, and are divided into physical, biological or chemical (Ding et al., 2024, p. 2; Helldén et al., 2006, p. 12). Ex-situ remediation techniques consist of excavating the contaminated soil and transporting it to another site for treatment, whereas in On-site scenarios, the excavated contaminated soil gets treated at the site of excavation. In in-situ remediation techniques, the contaminated soil gets treated at the site without any excavation (Helldén et al., 2006, p. 12). After their Åtgärdsplan Näsudden 2022, Afry and Sweco concluded that using an On-site or In-situ treatment method were the preferable way, to limit the environmental and economic impacts related to ex-situ transportation and treatment (Geisler, 2025, p. 14). This chapter investigates commonly used techniques to remediate heavy metal contaminated soils in Sweden.

2.3.1 Physical remediation

This chapter investigates physical remediation techniques where the contaminants are physically removed to immobilize and limit them from spreading and leaching, either by excavation or by encapsulation.

2.3.1.1. *Excavation and landfilling*

Contaminated soil waste with high levels of heavy metals is often excavated and landfilled in Sweden. This method consists of digging up the contaminated topsoil and transporting it to dumpsites for longer periods of landfilling. The excavated top soil then oftentimes has to be replaced with non- or less-contaminated clean soil (Papageorgiou et al., 2021, p. 2). At the Näsudden site, there is also a heavy occurrence of large rocks underneath the mineral layer of the soil, which needs to be removed or crushed at the site before excavation (Sweco, 2025b, p. 8).

Another factor that limits the viability of excavating and landfilling the contaminated soil waste are the toxicity of the waste versus the country regulations. According to measurements made on the top-soil layer, the Total Organic Carbon (TOC) value exceeds the Swedish EPA reference value for acceptable limits for waste that can be accepted by landfills. The measured value must not exceed 3%, yet the TOC levels reach approximately 6% at various measure points at the location (Geisler, 2025, p. 21; Naturvårdsverkets Föreskrifter Om Deponering, Kriterier Och Förfaranden För Mottagning Av Avfall Vid Anläggningar För Deponering Av Avfall; NFS 2004:10, 2005, p. 7), thus a permission to handle this waste must be received beforehand (Geisler, 2025, p. 21).

However, as the fine fraction of the top layer are the only soil consisting of critical levels in regard to the Avfall Sverige FA reference values for As, Cu, Pb and Zn (Skellefteå Kommun, 2022a; Sweco, 2025a, p. 20; Tyréns AB & Skellefteå Kommun, 2017, pp. 22-27 Bilaga 4), it is assumed that the fine fraction is the only material from the excavation that needs to be landfilled as hazardous waste. This means the remaining soil at the total excavated depth of 0.4 m might be reusable at the site. It is however important to note, that landfilled soil waste still pose a threat of leaching heavy metals ex-situ (Wan et al., 2026, p. 3).

Transporting the hazardous soil may plays a large role in the environmental and economic impacts of the solution, as the most common vehicle used to transport large amounts of contaminated soil is through heavy trucks. These trucks can carry around 15-30 tonnes of soil, and determining the exact amount of transports needed for the project can be challenging (Helldén et al., 2006, p. 14). For the Näsudden project, it has been approximated that 3300 truckloads driving a 240 km round trip from the site to the Dåva landfill in Umeå (Geisler, 2025, p. 24) is needed to carry the large amounts of hazardous waste, which could result in transportation costs up to 200 million Swedish Kronor (SEK) (Geisler, 2025, pp. 10–11). Despite its disadvantages, it is still a preferrable method to use when other remediation techniques are not viable or possible, as it is a fairly simple, robust way to handle and control contaminated soil (Geisler, 2025, p. 27).

As excavation and landfilling is the traditional method of soil remediation in Sweden and may end up as a worst-case scenario for Skellefteå municipality where the fine fraction soil cannot be reused, it has been included as a potential remediation technique in Scenario 1.

2.3.1.2. Containment/barrier

Using containment technology to contain contaminated soil in barriers or covers is an effective way to shut in heterogenous soil with mixed contaminants. The method does not, however, treat or remove the contaminants, as it simply contains them inside the barrier or cover, requiring long-term monitoring of leachate and stability (Fernández Rodríguez et al., 2014, pp. 344–345). To minimize the leaching, it is preferred to encapsule the contaminated soil within a barrier, as it limits the accessibility of groundwater flows for the contaminants (Sethi & Gupta, 2021, p. 9).

In 2025 investigations on constructing a noise barrier without a cement foundation was conducted. This noise barrier will be located north of the industrial compound, containing three different noise barrier parts as shown in Figure 4 and Figure 5. These results were deemed promising, as it would provide a solution to encapsule the excavated contaminated soil in-situ without having to transport it off the site (Geisler, 2025, pp. 14–21).

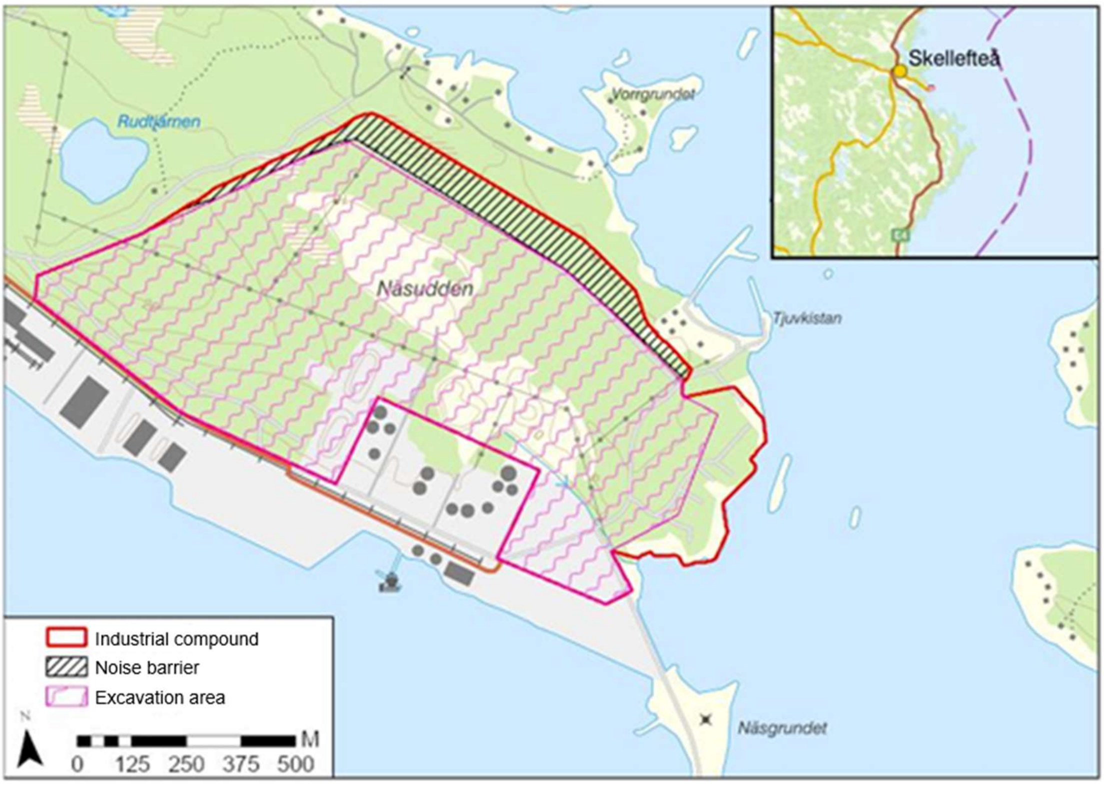

Figure 4: Map showcasing the location of the noise barrier at Näsudden planned industrial compound marked in red (Sweco, 2025b, p. 6)

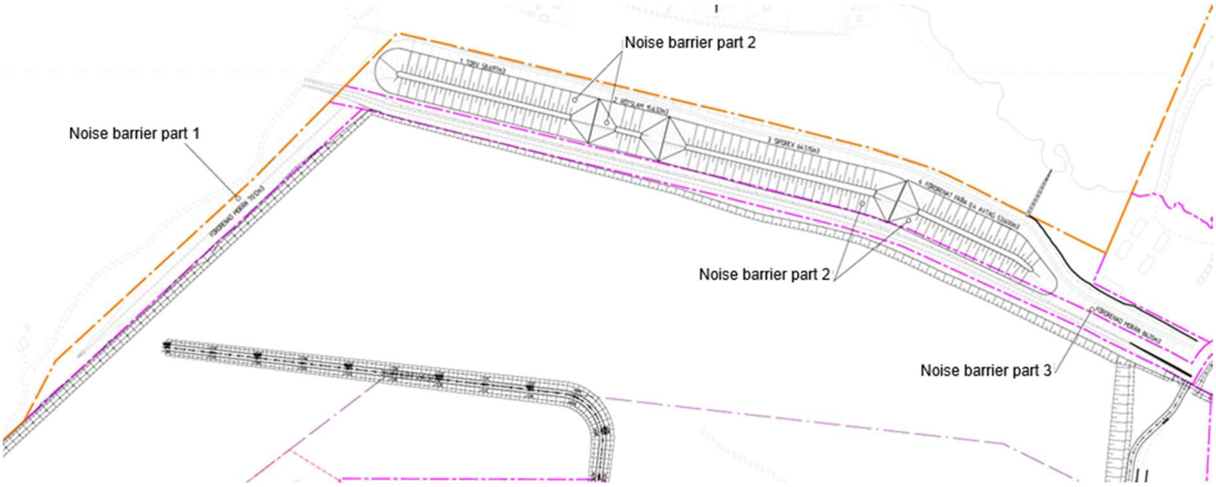

Figure 5: Map showcasing the location of the noise barrier at Näsudden and its three different parts (Geisler, 2025, p. 44; Sweco, 2025b, p. 6).

The industrial compound at Näsudden is expected to reach noise pollution levels of approximately 45 dBA during all hours of the day, which is above regulatory nighttime limits of 40 dBA. The recommended height of the noise barrier were set to 12 m as it could potentially limit the noise pollution in close proximity to 39 dBA (Sweco, 2025a, pp. 11–18) while providing privacy to nearby residents. The noise barrier are planned to consist of peat, sewage sludge, siporex, moraine and rock debris from the site, as well as the fine- and coarse fraction soil excavated from a 0.4m depth excavation, as well as external organic topsoil, as shown in Table 3 together with each materials respective volume and total weight (Geisler, 2025, pp. 20–22 & pp. 43–45; M. Lindmark, personal communication, March 26, 2026).

Table 3: Total amount of volume and weight needed of each material to construct the noise barrier (Geisler, 2025, pp. 20–22 & pp. 43–45; M. Lindmark, personal communication, March 26, 2026).

Material	Amount needed for noise barrier (m^3)	Amount needed for noise barrier (tonnes)	Used for in noise barrier
*Fine fraction**	5.40E+04	1.00E+05	Encapsulated inside core of barrier.
Rock debris	2.14E+04	6.09E+04	Draining top layer, 0.3 m.
Siporex	6.45E+04	3.87E+04	Encapsulated inside core of barrier
Moraine	1.81E+05	3.87E+05	Confining layer, 1.5 m. Embankments. Leveling out-layer at bottom of barrier. Contaminated moraine Encapsulated inside core of barrier.
Sewage sludge	1.56E+04	1.60E+04	Encapsulated inside core of barrier.
Peat	5.87E+04	1.76E+04	Encapsulated inside core of barrier.
External topsoil	2.50E+04	4.01E+04	Slope cover, 0.3 m. Density 1600 kg/m^3 (Snabbgrus, 2026; Y-Kross AB, 2026).
Total	4.20E+05	6.60E+05	

*Note: * Will only be encapsulated inside noise barrier in Scenario 2 and 3. Will be transported for landfilling in Scenario 1.*

Leachate tests done prior to the noise barrier planning by Tyréns in 2017 concluded that, although the leachability of the heavy metals were deemed low for the top soil layer, the leachability of As elevated when the fine fraction soil were mixed with siporex (Tyréns AB & Skellefteå Kommun, 2017, p. 15).

Although the approval of utilizing this noise barrier as a remediation technique is at the time of the study still pending, it is assumed that it will be implemented at the site, with or without the usage of the fine fraction soil, and were thus included in Scenario 1, Scenario 2, and Scenario 3 for further LCA and economic analysis.

2.3.1.3. *Thermal remediation*

Thermal remediation is a technique that utilizes heating at high temperatures (70-1100°C) to evaporate the contaminants of the soil, putting the contaminants in a gaseous state, which can then be extracted. It is commonly used to remediate soils with elevated levels of Chlorinated aliphatic hydrocarbons (CAH), but has proven to work for heavy metals as well (Svenska Geotekniska Föreningen, 2026f, 2026g).

The remediation process be done either ex-situ, or in-situ (Svenska Geotekniska Föreningen, 2026f, 2026g). For ex-situ treatment, the soil is excavated and transported to an ex-situ treatment plant, where soil separation and pre-treatment occurs before remediation in a furnace (Svenska Geotekniska Föreningen, 2026f). In-situ treatment removes the need for excessive contaminated soil transportation to an ex-situ treatment plant as the process can be done on-site, either by Thermal Conductive-, Electrical Resistance-, Steam- or Radio Frequency heating (Svenska Geotekniska Föreningen, 2026g).

Thermal remediation techniques are effective at treating fine fraction layers at a short treatment period, however, the process is energy intensive as high temperatures needs to be maintained, yet the trade-offs between the time needed for treatment and energy requirements are better fitted for large-scale areas (Svenska Geotekniska Föreningen, 2026g).

The risks of using thermal remediation techniques for highly As contaminated soil are high. While higher temperatures can reduce the amount of mineral As, it also tends to generate gaseous As via volatilization, which condenses when the temperature gets lowered. At the same time, thermal remediation changes the pH-value of the soil structure. In this condensed state, and with higher pH, the leachability and mobility of the As in the soil structure becomes higher (Zhou et al., 2024, pp. 207–214). For in-situ treatment, the shallow groundwater flows at the Näsudden area could potentially cool the temperatures even further, enhancing the leachability and hindering the treatment process (Svenska Geotekniska Föreningen, 2026g; Tyréns AB & Skellefteå Kommun, 2017, p. 8).

Thus, using the technique ex-situ could reduce the environmental and health risks. However, due to the large amounts of fine fraction soil that needs to be transported for treatment, without infrastructure in close proximity (Svenska Geotekniska Föreningen, 2026f) and the risks of treating high As contaminated soil, the remediation technique were excluded from any further investigation in the LCA and economic analysis.

2.3.2 Biological remediation

Biological remediation techniques are utilizing plants, microorganisms or other organic agents to immobilize contaminants, such as heavy metals within the soil structure, as they utilize the contaminants as energy to grow. It is an eco-friendly, although time consuming process for soil remediation, with potentially limited results for colder climates (Adebayo et al., 2025, pp. 1–2; Svenska Geotekniska Föreningen, 2026b). This chapter investigates the most common type of biological remediation: Phytoremediation.

2.3.2.1. Phytoremediation

Phytoremediation is a technique that utilizes different biological processes such as accumulation and degradation, where plants can immobilize contaminants within the soil. The most common method used for heavy metal heterogenous contaminated soils are phytostabilization and phytoextraction (Y. Zhang et al., 2023, pp. 1–2) and is done in-situ, where the contaminants are higher at the shallow top layer of the soil (Svenska Geotekniska Föreningen, 2026b).

Phytostabilization is more commonly used for remediation of heavy metal contaminated soils, where the contaminants are adsorbed to the plants roots, binding the contaminants to the soil which hinders further spread (Svenska Geotekniska Föreningen, 2026b).

Using phytoextraction, the plants roots absorbs the contaminants, which then transports to the above ground part of the plant, and can thereafter be extracted, effectively reducing the levels of contaminants within the soil (Svenska Geotekniska Föreningen, 2026b). This technique has also been proven effective at treating heavy metals such as As using *P.vittata,* and plants such as *Salix viminalis*. *Salix dasyclados* have been proven effective at treating Cd, Pb and Zn. The plants can after extraction be transported for pre-treatment and reused as biomass for energy production, or be incinerated or composted before disposal (Adebayo et al., 2025, p. 16; Svenska Geotekniska Föreningen, 2026b; Wan et al., 2026, pp. 2–7).

The technique has its advantages as an eco-friendly solution to heavy metal contaminated soil, however, reducing the contamination levels to acceptable limits can take several years, or decades for highly contaminated site (Wan et al., 2026, pp. 2–7). The time constraints of the project, combined with the cold climate of northern Sweden where the Näsudden area is located, which limits the growing potential of the phytoremediation plants (Svenska Geotekniska Föreningen, 2026b) have thus excluded the remediation technique from further investigation in the LCA and economic analysis.

2.3.3 Chemical remediation

This chapter investigates different chemical remediation techniques, both traditional and nontraditional: Biochar remediation, Stabilization/solidification as pilot tested previously at the area, and soil washing.

2.3.3.1. Biochar remediation

Using biochar to remediate contaminated soil are an alternative non-traditional method of waste management. Biochar is created from thermochemical conversion of biomass feedstock using techniques such as pyrolysis, gasification or torrefaction, and has absorbing properties when applicated to contaminated soil (Matuštík et al., 2020, p. 2; Papageorgiou et al., 2021, p. 2). It is mainly used to improve the health of the soil and increase crop growth, but has shown a great potential for contaminant removal, where it may remove up to 80% of some heavy metals (Nguyen et al., 2023, p. 2).

The heavy metals get absorbed by the biochar porous structure, and its efficiency depends on the structure and characteristics of the biochar, and how it is produced (Nguyen et al., 2023, pp. 2–3) . As it is a product from waste or wastewater treatment, it can be derived from different types of available feedstocks, such as sewage sludge, organic municipal waste or wood waste. It is thus important to understand the availability near the contaminated area, as well as the best suited type of biochar to use for the purpose. It is also important to note that some waste feedstocks might contain contaminants, which might not be removed from biochar production (Matuštík et al., 2020, pp. 5–9) and should thus be avoided to prevent further contamination. If done properly, the process could function as a sequestration method of carbon dioxide (CO_2), potentially acting as a carbon sink to achieve net-negative CO_2 emissions, and having lower environmental impacts than traditional extraction and landfilling (Ibrahim et al., 2017, p. 19525; Papageorgiou et al., 2021, p. 10, 2022, p. 5).

Although its potential of high contaminant removal when added to soil,, the solution has been proven to sorb Cu, Hg, Ni, and Zn more effectively than negatively charged heavy metals such as As using wood waste biochar (Papageorgiou et al., 2021, pp. 2–11). The effectiveness of As removal depends however on the soil and biochar properties, and using biochar with optimal pore size optimization could potentially increase the removal rate, where biochar produced using MSW at lower temperatures (300-500 °C) could be a more valid solution for heavily As contaminated soil waste (Vithanage et al., 2017, pp. 222–224).

However, due to the projects time constraints, and the high amount of As within the area, using biochar remediation at Näsudden has not been included as a potential remediation technique in the LCA and economic analysis.

2.3.3.2. Stabilization/solidification

If the contaminants are not to be removed from the soil, the contaminated soil can be valorised in the form of stabilization and solidification, either ex-situ or in-situ. When this process is done in-situ it is oftentimes used to limit further spreading of the contaminants by physically encapsuling or chemically remediate the contaminated soil waste, minimizing the need for ex-situ transportation (Holm et al., 2007, p. 7; Svenska Geotekniska Föreningen, 2026e). This is oftentimes an uncertain solution, as the long-term effects of these stabilized structures and its durability are difficult to foresee, and secondary release of metals by leaching pose a risk (Jia et al., 2026, p. 2; Svenska Geotekniska Föreningen, 2026e).

In 2023, Afry and Luleå University of Technology (LTU) conducted a pilot experiment of using this method to valorise the contaminated soil waste at Näsudden as shown in Figure 6. The contaminated soil were separated into fine- and coarse fraction, where the hazardous fine fraction were mixed with concrete and ash to build a foundation to the previous mentioned noise barrier, thus removing the need for ex-situ transportation to landfill (Bjuhr & Andreas, 2023, pp. 10–13; Geisler, 2025, p. 14).

Figure 6: Photograph of pilot scale noise barrier, 3 months after stabilization and solidification (Bjuhr & Andreas, 2023, p. 15)

The solution were deemed both successful and unsuccessful, as the high compactness and low hydraulic conductivity of the noise barrier limited leaching, but the health risks of handling the dry fine fraction, ashes and cement mix were deemed too high (Bjuhr & Andreas, 2023, pp. 38–40). The high amounts of ash and cement needed for mixing the high amounts of fine fraction were also deemed unsuitable and cost ineffective, and mixes with higher amounts of organic material lowered the structures durability (Geisler, 2025, p. 14; J. Wellenius & O. Rydlinge, personal communication, March 24, 2026) making the method obsolete. This remediation technique was thus excluded from any further LCA or economic analysis.

2.3.3.3. Soil washing

Soil washing is an effective remediation technique for larger scale heavy metal contaminated soil (Amato et al., 2026, p. 276; Svenska Geotekniska Föreningen, 2026d; Wei et al., 2023, p. 1) and consists of two processes: first and foremost by extracting the contaminated soil, and separating the contaminants from the soil, which can be treated ex-situ or on-site using other remediation techniques. Secondly the contaminated soil gets treated, ex-situ or on-site, using water-soluble chemicals, causing the contaminants to dissolve from the soil mixture and transfer into the liquid of the washing agents (Fernández Rodríguez et al., 2014, p. 346; Huang et al., 2026, p. 2). It can be an effective solution to remove and recover the contaminants in a shorter amount of time (Qiu et al., 2026, pp. 1–2), and has been proven to work in both pilot scales and larger scales of contaminated soil (Wei et al., 2023, p. 1).

Choosing which type of chemicals to use depends on the structure of the contaminated soil, such as its pH, texture, inorganic and organic matter content, as well as the properties of the chemical. Inorganic and organic acids, and chelating agents are commonly used and effective at treating heavy metal contaminated soils. Other types of commonly used washing agents consists of bases, salts bases, redox agents and surfactants (Huang et al., 2026, p. 2; Kim et al., 2016, p. 275; Qiu et al., 2026, p. 1). Water could be used as a washing agent alone, however, due to the lack of solubility from metals, it is ineffective using it to wash heavy metal contaminated soil (H. Zhang et al., 2022, pp. 2–3). If the chemicals used are to be recirculated within the system, it is important that the chosen chemicals have limited biodegradability (Dermont et al., 2008, p. 23).

As the Näsudden sites soil structure is heavily contaminated with As, Pb, Cu, and Zn (Geisler, 2025, p. 12), picking a suitable washing reagent that does not cause secondary pollution is thus key. Typically, the soil washing process should aim to remove 70-80% of the contaminants, or around 50% if landfilling the soil is unfeasible (CRC for Contamination Assessment and Remediation of the Environment, 2018, pp. 6–7). There are several viable solutions to correct chemical usage, they do however tend to have their advantages and disadvantages. For example, using a alkali solution, such as sodium hydroxide (NaOH) can be effective at removing As, but might increase the pH within the soil, and inorganic washing agents, such as acids, bases, or salts, could destroy the organic structure of the soil, preventing its reusability as nutrient land refill (Wang et al., 2024, p. 1175; H. Zhang et al., 2022, pp. 8–13; Zheng et al., 2022, p. 4). Using a chelating agent, such as Ethylenediamine-tetraacetic acid (EDTA), is effective at removing Pb, Cu and Zn, but is ineffective at removing As (Dermont et al., 2008, pp. 16–23; Teng et al., 2020, pp. 23224–23228). The availability of said chemicals and budget of the investment is also important taking into account (H. Zhang et al., 2022, p. 13).

For heterogenous contamination structures, such as the one at Näsudden, it is common to combine different washing agents for an increased removal efficiency (Zheng et al., 2022, pp. 15–17). In their study on soil washing solution effectivity, Cho et al., 2020, pp. 7–10 achieved removal efficiencies of As, Cu, Pb and Zn of 70.5%, 79.6%, 80.1% and 71.2% respectively for contaminated fine fraction soil (± 0.106 mm) by using a mixture of equal parts sulfuric acid (H_2SO_4) and phosphoric acid (H_3PO_4), with a Liquid-to-Solid ratio (L/S) of 7:1 (Cho et al., 2020, pp. 7–10). Even if the usage of only inorganics in the soil washing process would destroy the remediated fine fractions soil structure (Zheng et al., 2022, p. 4) the plan is to encapsulate the fine fraction inside the noise barrier at Näsudden (Geisler, 2025, pp. 14–21), which lowers the need for an organic end product.

The soil washing process can be done using a mobile soil washing system. This solution has been proven effective in conducting an ex-situ solution on-site, to clean the soil of heavy metals without having to transport the soil to another site. This limits the process steps to excavation, soil remediation, solid- and liquid separation, residue disposal or treatment and deposition of the soil cleaner (Semer & Reddy, 1996, pp. 46–48). A soil washing station may treat up to 50 tonnes of soil per hour (Svenska Geotekniska Föreningen, 2026d), and depending on the uptime of the mobile washing system, it might align with the time frame set for the Näsudden project. A similar process was previously investigated by ÅF Infrastructure AB and Vallentuna municipality to treat Polycyclic Aromatic Hydrocarbons (PAH) contaminated soil. The process was deemed plausible for the occasion and the site, and it was suggested that further research should be made, including pilot scale testing (Jansson, 2019, pp. 3–31). However, it is important to note that soils with high organic content, and heavy metals of fine fractions are harder to remediate using soil washing due to the increased adsorption of the heavy metals (Cho et al., 2020, pp. 4–7).

Due to its potential regarding remediating heterogenous heavy metal contaminated soil, and the availability of mobile on-site soil washing in Sweden and Europe, the remediation technique has been included in Scenario 3 in the LCA and economic analysis.

2.3.3.4. Soil flushing

Soil flushing is a technique similar to soil washing that can be used in-situ by pumping water-soluble remediation additives directly into the contaminated soil. The pumped solution, consisting of water mixed with chemicals or acids, basis or other pH altering liquids improves the mobility or solubility of the contaminants within the soil. The flushed contaminated fluid can thereafter be extracted from the site for ex-situ disposal or treatment (Fernández Rodríguez et al., 2014, p. 346; Svenska Geotekniska Föreningen, 2026c).

The technique is however limited in Sweden, as the availability of soil flushing infrastructure is low, and the time frame needed for the heterogenous contaminants to be remediated is uncertain. The soil structure at Näsudden can also be considered too heterogenous (Geisler, 2025, p. 8; Sweco, 2025b, pp. 8–9) for the technique to be deemed viable, as the contaminant removal efficiency would be lower compared to more homogenous soil structures (Ai et al., 2026, p. 5, 2026, p. Appendix A:5; Svenska Geotekniska Föreningen, 2026c), and has thus been excluded from further LCA and economic analysis investigation.

2.4 Skellefteå municipality sustainability goals

The city of Skellefteå aims to be at the forefront when it comes to sustainable innovations and circular economy. This includes being a test subject for new innovations and technologies for sustainable solutions (Skellefteå Kommun, 2022b, p. 20), it is thus suitable to try alternative and innovative remediation techniques for the heavy metal contaminated soil at the Näsudden area.

Its political goal is to reach 90 000 citizens by 2030 by implementing sustainable and inclusive strategies, to make the city a more attractive place to live and thrive (Skellefteå Kommun, 2022b, pp. 5–9), and constructing the industry complex at Näsudden could potentially provide the people of Skellefteå more job opportunities within a sustainable field.

Sustainable collaborations with other stakeholders and municipalities, both locally and globally, should be prioritized as a way of working together towards a sustainable future (Skellefteå Kommun, 2022b, p. 21), through larger investments in social and environmental development (Skellefteå Kommun, 2022b, pp. 9–10).

Focusing on sustainable construction, (Skellefteå Kommun, 2022b, p. 12) and sustainable transportation options transporting goods and waste, with an emphasis on using railroad and naval transport when possible should be prioritized (Skellefteå Kommun, 2022b, pp. 22–25). Although the planned transportation route for the contaminated soil waste is through heavy trucks (Geisler, 2025, p. 24; J. Wellenius, personal communication, November 27, 2025), the option of using railroad or naval transport exists at the area and at the Dåva landfill (J. Wellenius & O. Rydlinge, personal communication, March 2, 2026).

By following these sustainability goals, sustainable alternative remediation techniques both tested on larger scale and on pilot scale were investigated with the opportunity to collaborate with both Swedish, and European stakeholders.

2.5 Life Cycle Assessment and Life Cycle Costing

The sustainability aspect of choosing a potential remediation technique for contaminated soil waste is oftentimes overlooked (Amato et al., 2026, p. 732). Using LCA is an effective tool to analyse the environmental impacts of waste handling and remediation (Papageorgiou et al., 2021, p. 2) and may thus be used to determine possible alternative pathways deemed more sustainable for handling the heavy metal contaminated soil at Näsudden by mapping its full life cycle (Amato et al., 2026, p. 732).

An LCA analysis allows for further investigation of all steps within the system, from extraction to remediation or disposal. It follows an international standardised work method and in line with the frameworks of ISO 14040 and 14044 standards (European Commission, 2010, p. iv). This framework proposes the LCA study to be conducted using four main steps: Goal and Scope definition, Life Cycle Inventory Analysis (LCI), Life Cycle Impact Assessment (LCIA) and Interpretation (European Commission, 2010, p. 1).

Setting the goal and scope definition of the project is the first part of an LCA, and works as a way to define the goals and reasonings beforehand and along the way of the study (European Commission, 2010, p. 11; Matuštík et al., 2020, p. 2).

Setting a functional unit (FU) for the project is done to define the qualitative and quantitative functions of the systems, as well as its reference flows to calculate and compare different systems performance between each other (European Commission, 2010, pp. 59–63). For the study to be correct, the FU must stay the same between scenarios (Olivier et al., 2016, p. 37) and for this this case study, it is used to compare environmental and economic performance, as well as human health impacts between different types of soil remediation techniques. In their literature review study on LCA connected to soil and groundwater remediation techniques, Lemming et al. (2010, pp. 115–119) found that the FU is oftentimes connected to soil volume treated, either in tonnes or m^3 over either a set time period or to reach a set limit of contaminant levels.

A system boundary should be set to determine the steps of the systems lifecycle that should be included for a possible comparison between the scenarios. It is thus important to keep all affected scenarios within the same system boundaries (European Commission, 2010, pp. 100–101; Olivier et al., 2016, p. 37)

The next step after determining the goal and scope of the study is the LCI, which is considered the main part of the LCA and paves the way for the LCIA by determining or estimating the inputs needed for the systems life cycle material flow. This includes gathering data related to the scenarios (Blanck et al., 2016, p. 6; European Commission, 2010, p. 12), either by primary site-specific or secondary sources.

The LCIA is according to ISO14040 the next step after the goal and scope, and LCI has been defined. It consists of five steps to determine the impact categories, indicators and characteristics. For the study to follow best practice and align with the framework of 14040, the three first steps of selecting impact categories, assigning LCI results and calculation of indicator results to said categories must be made (Hauschild & Huijbregts, 2015, pp. 4–6). This step also defines the methods to be used to reach significant results, and how they are to be interpreted (European Commission, 2010, p. 12).

After all previous steps have been made, the results of the LCA are to be interpreted. This step determines if the research questions have been answered according to the defined goal of the study, as well as giving a conclusion and recommendations for further research (European Commission, 2010, p. 285). The reliability of the results can be checked using for example a sensitivity analysis. The interpretation is also used to determine if the methods, inputs and assumptions have been consistent throughout the study (European Commission, 2010, pp. 285–300)

Lastly, to compare the trade-off between the environmental, human health and economic impacts between the scenarios connected to soil remediation, combining the LCA study with an economic analysis based on the basics of LCC analysis can strengthen the results even further, while providing valuable insight for decisionmakers and stakeholders (Ding et al., 2024, p. 12; Jeon et al., 2025, p. 2).

In their study on sustainability assessment of waste recycling in low-impact development, Jeon et al. (2025, pp. 1–10) used the combined method of LCA and LCC with successful results. Their end results were presented using a sustainability index, comparing the emissions to cost ratio, successfully showcasing the environmental and economic benefits between their two scenarios. The LCC is a tool to analyse the costings within all processes of the scenario systems lifecycle, in order to compare the scenarios between each other (Ding et al., 2024, p. 12). The FU stays the same in the LCC and LCA (Yang et al., 2025, p. 4), as the scenarios are based on different remediation techniques at the same location within the same system boundaries.

3 METHOD

To conduct this study, a mix of qualitative and quantitative data and information gathering were used. The material gathered from this built the foundation for the LCA and economic analysis. An attributional approach was used across modelling, data gathering, and simulation, thus only including relevant data connected to all scenarios processes, such as measured site-specific data, historical or recent data from databases, similar case studies or service providers. The models of the scenarios were created to include all relevant processes within the system boundaries, including those related to reference- and functional unit flows, predicting how the systems will work (European Commission, 2010, p. 71). By using an attributional over a consequential approach, the LCA only determined the environmental, human health and economic impact of the life cycle of each scenarios system, and not the impacts caused outside of the system boundaries (Ekvall, 2020, pp. 4–5).

3.1 Qualitative collection

A thorough literature review and interview-based research was made both to understand the subject being researched, and to find relevant information and solutions to alternative waste management, remediation and valorisation methods.

3.1.1 Literature review

To conduct the literature review mentioned in *Chapter 2 Literature study*, peer-reviewed articles, journals, reports and documents regarding similar case studies, alternative waste management, remediation and valorisation methods, and legislations and policies relevant to the study were gathered and reviewed through publicly available databases such as Google Scholar, Elsevier Scopus and Springer Nature Link using certain keywords, such as "contaminated soil remediation" and "large-scale soil remediation". Publications and documentations regarding the project and the location provided by Skellefteå municipality were studied to understand site-specific challenges and possibilities related to soil waste management and remediation.

3.1.2 Interviews and inquiries

During the period of the study, regular interviews and communication were made with supervisors Johanni Wellenius and Olov Rydlinge, working as Environmental inspectors at Skellefteå municipality, through their expertise on the Näsudden project. This information was used to structure the study, learn more about the limitations and challenges connected to the case, and previously failed methods used.

Mikael Lindmark, project manager at Skellefteå Municipality, and Christer Svensson, project manager at Skellefteå Municipality, which were previously a part of the stabilization project workforce at the site, where interviewed mainly regarding the processes, costings and machinery within the project, to gather information regarding the questions:

- What type of machinery will be used for excavation, separation, transporting soil and rocks in-situ, crushing, and ex-situ transportation of hazardous materials?
- What type of fuel will mainly be used for said machinery?
- What type of explosives will be used for blasting the rock mountains at the area?
- What is the process for handling or reusing potential excess excavated material?

To gather relevant information regarding machinery fuel and energy consumption connected to separation, an inquiry via e-mail were sent to a representative at Rubble Master HMH GmbH with the questions:

- What is the average diesel fuel consumption of the RM HS5000M Cummins Stage 5 separator, in L/h?

Relevant information and data regarding mobile soil washing units were requested via website inquiries and e-mail to service providers in Sweden and Europe, and relevant faculties in Sweden, such as the Swedish Defence Inspectorate for Medicine and Environmental Health and the Swedish Geotechnical Institute, with knowledge and expertise within the subject, with questions such as:

- What is the average fuel and energy consumption of a mobile soil washing unit?
- What common washing agents are available for As, Cu, Pb and Zn contaminated soil?

Through these interviews, inquiries and questions, a more robust process flow was constructable. The information and data provided played a key role in the methodology and modelling of the LCA and economic analysis and made the results more detailed and relevant to the case study.

3.2 Life Cycle Assessment

Due to the availability of primary data provided by Skellefteå municipality in the forms of in-situ measurements made at Näsudden, the input variables were deemed reliant enough to reflect the conditions at the site. Secondary data collected for parameters where primary data were unavailable and used, which may have increased the uncertainty of the end results (Ai et al., 2026, pp. 2–4). The results of the LCA analysis are therefore purely theoretical and should be interpreted as such.

3.2.1 Goal and Scope definition

The limitations set for the study during the Literature Review research excluded any alternative solution not fitting for the project, setting a FU, naming the reasoning behind the study, stating comparisons to similar case studies, as well as identifying the instances involved in the study (European Commission, 2010, p. 2), consisting of the Skellefteå municipality as an assigner of the project and Mälardalen University as supervision and guidance.

Before the FU was set, the functions of the system were defined (Olivier et al., 2016, p. 26), where processes specific to the scenarios, such as excavation, separation and transportation were set as foreground processes, and secondary inputs, such as electricity and water inputs were set as background processes.

The scenario criteria were based on were used as a guideline to choose suitable pathways depending on the site properties and guidelines from the Swedish Environmental Agency and the city sustainability goals. It were also taken into account that all scenarios had to use the same FU and stay within the same system boundaries (Olivier et al., 2016, p. 37).

A goal was set to gather data from 2010-2026, with preferable origins from Sweden, as data parameters gathered from outside the country would potentially lower its quality. The technological limitations were set to stay consistent with the price data availability of the economic analysis, and vice versa, as well as being relevant to each separate scenario system using data points from operating companies and manufacturers. If no publicly available data were to be found or could gathered from personal communication with said companies or manufacturers, data would be gathered from similar case studies or relevant databases.

3.2.1.1. Analysis to structure scenarios

Through the literature review, different remediation techniques were investigated and compared. The result from this comparison is shown in Table 4. These showcase the different investigated remediation techniques regarding the soil structure, limiting spread of contaminants, contaminant heterogeneity within the soil, the large volume of soil that needs to be treated, and the time frame of 1-2 years which the remediation should be completed.

Table 4: Remediation techniques weighed against the proposed site criteria to treat the contaminated soil at Näsudden.

	Site criteria				
Technology	***Soil structure***	***Spread limitation***	***Contaminant heterogeneity***	***Volume capacity***	***Time frame***
Excavation and landfill	x	x	x	x	x
Phytoremediation	x	x	x	x	
Biochar remediation	x			x	
Soil washing	x	x	x	x	x
Soil flushing		x	x	x	
Thermal treatment	x			x	x
Stabilization/solidification	x	x	x		x
Containment/barrier	x	x	x	x	x

This investigation and comparison built the structure of the scenarios which were to be modelled. The only technique deemed plausible, disregarding the two proposed scenarios of landfilling, and containment using a noise barrier, based on the site criteria were soil washing.

The Containment/barrier technique has been investigated on a pilot scale and has been approved by Skellefteå municipality as a solution that has to be included regardless of remediation method chosen for the project, as the noise pollution must be mitigated, and to valorise the excess amount of excavated material.

Thus, three different scenarios were defined, in agreement with Skellefteå municipality:

- Scenario 1: Landfilling (Chapter 3.2.1.3).
- Scenario 2: Noise barrier encapsulation (Chapter 3.2.1.4).
- Scenario 3: Soil wash and Noise barrier encapsulation (Chapter 3.2.1.5).

More information regarding these three chosen scenarios can be found in Chapter 3.2.1.4. Scenario 1: Landfilling, Chapter 3.2.1.5. Scenario 2: Noise barrier encapsulation and Chapter 3.2.1.6. Scenario 3: Soil wash and Noise barrier encapsulation

3.2.1.2. System boundaries

All scenarios were modelled according to a cradle-to-grave approach to define where the life cycle of the soil waste begins and ends. For this case, the cradle is the extraction of the material, meaning the excavation of the heavy metal contaminated soil, whilst the grave of the system is when the heavy metal contaminants of the soil has been immobilized in terms of critical levels. Due to the importance of all scenarios being within the same system boundaries, all three scenarios started with the excavated soil from the three different excavation processes: Excavation 0.4m depth, Rock excavation/blasting and Excavation other, and ended with the time horizon when the heavy metal contaminants above critical levels were immobilized. This is including taking the end treatment in the landfill for Scenario 1, and Scenario 3, assuming the contaminant is treated at the disposal, and abandoned after a certain time period (Baumann & Tillman, 2004, pp. 79–80). For Scenario 2, it was assumed that the contaminants were considered immobilized after the hazardous soil had been encapsulated. A foreground and background system approach were taken for all scenarios, to define processes specific to the system as foreground, such as excavation, transportation and treatment. The background systems were defined as the processes being supplied upstream and downstream by a supply chain, such as electricity and water (European Commission, 2010, pp. 96–99).

The FU of this case study were set to “1 tonnes of hazardous fine fraction”, converted from a total weight of 100000 tonnes excavated heavy metal contaminated fine fraction to simplify the comparison to similar case studies (Bisinella et al., 2024, p. 57), and to consider the fine fraction soil waste measured above FA levels. This approach were made based on the LCA literature review study conducted by Lemming et al. (2010, pp. 115–119). There are multifunctional processes within the system for all scenarios, since there is more than one material flow due to multiple excavation points and external soil being transported to the site. These material flows are considered as reference flows, and has been stabilized according to the FU in order to keep the mass balance within the system (European Commission, 2010, pp. 65–67), as shown in Table 5. These stabilized values where used for their respective material generation input in the Environmental Assessment System for Environmental Technologies (EASETECH) LCA software (Technical University of Denmark, 2019).

Table 5: Stabilized processes from their original amount into their converted amount based on the functional unit.

Process	Amount	Converted	Unit
Excavation 0.4 m depth	5.00E+05	5.00	tonnes
Excavation and blasting	3.24E+06	32.40	tonnes
Excavation other	6.86E+05	6.86	tonnes
External (excluding replacement soil for missing fine fraction)	4.01E+04	0.40	tonnes
External (including replacement soil for missing fine fraction Scenario 1)	1.40E+05	1.40	tonnes
External (including replacement soil for missing fine fraction Scenario 3)	5.51E+04	0.55	tonnes
Coarse fraction	4.00E+05	4.00	tonnes
Functional unit, based on Fine fraction	1.00E+05	**1.00**	**tonnes**

Due to the municipality best interest to investigate the best suited remediation technique to immobilize the contaminated fine fraction, a change of impact between the scenarios are assumed to occur, meaning several processes have been assumed to be the same between the three scenarios. These include:

- Transportation of mechanics and/or chemicals to the site before treatment are assumed to be the same.
- All scenarios are assumed to include the same parameters for excavating and transporting the soil.
- All scenarios consists of blasting the rock mountains located at the site with explosives, and the resulting debris of rocks will be crushed and reused as soil and noise barrier refill (Sweco, 2025a, pp. 21–22). As this method is related to removing mountainous areas to construct the industrial complex and would be needed regardless of remediation technique, it has been assumed to be the same for all scenarios.

- All scenarios include soil separation to separate the fine- and coarse fraction soil. This is planned to be done on-site with a mobile sorting facility (Bjuhr & Andreas, 2023, p. 39; M. Lindmark, personal communication, March 26, 2026). It has thus been assumed that this process are the same across all scenarios.

Investigations at the area have concluded that excavated soil might need to be dewatered before any treatment or transportation can be made (Sweco, 2025a, p. 20), and according to interviews with Skellefteå municipality, no additional machinery would be used for said dewatering process, and would instead be dried naturally. It is also uncertain whether any dewatering process will be used at all (M. Lindmark, personal communication, March 26, 2026; J. Wellenius & O. Rydlinge, personal communication, March 2, 2026). Any dewatering process has thus been excluded from modelling.

All three scenarios have similar foreground processes before treatment or handling of hazardous fine fraction. These processes include “Excavation other”, “Excavation and blasting”, “Excavation 0.4 m depth”, “Separation”, “Dock”, “Noise barrier”, and “Land dock refill”. The machinery usage, transportation of input- and output material, and background inputs are assumed to be the same between all three scenarios for these processes.

The excavation consists of three different processes: Excavation 0.4 m depth, which includes the excavation of fine- and coarse fraction at a depth of 0.4 m at the site, Rock excavation and blasting, which includes the blasting and excavation of rock mountains at the site, and Excavation other, which includes the excavation at the locations of north- and south landfills at the site, excavation of peat these landfills, and excavation above rock mountains (Geisler, 2025, p. 20).

“Separation” includes the processes of separating the fine- and coarse fraction after excavating at a 0.4m depth. “Crushing” includes the process of crushing siporex (Geisler, 2025, p. 34), it has been assumed that separated coarse fraction will not need to be crushed before being used as fill or refill, and blasted and excavated rocks will be crushed by the excavation and blasting process, due to limited data availability and the uncertainty of resulting volume of large-scale rocks from the excavation processes. It has also been noted that the need for rock crushing will increase in wet conditions (M. Lindmark, personal communication, March 26, 2026), which increases the uncertainty of the volume needed to be crushed even further.

The “Noise barrier”-process includes all processes related to constructing said noise barrier, leachate generation, emissions to surface water and attenuation from leachate, and storage of carbon from leachate. The leachate generation is divided into two different processes: from noise barrier materials with heavy metal levels above FA reference levels, and from noise barrier materials with heavy metal levels above MKM but below FA reference levels. Both of these processes are modelled with a net infiltration of 493.9 mm/year as collected from the Bjuröklubb A measure station located southeast of the Näsudden site between 2022-2024 (SMHI, 2026), a height layer of 10.4 based on the structure of the core with the external topsoil excluded (Geisler, 2025, p. 43), and a bulk density of 1.852 tonnes/m^3 based on the density of the fine- and coarse fraction. All leachate from the noise barrier goes uncollected, as no leachate collection system is planned to be installed at the site. These uncollected leachate processes have been modelled according to the EASETECH database template (3b) Leachate - Uncollected - Emissions to surface water and attenuation which uses transformation rates of 100% for As, Cu, Pb and Zn into Arsenic, Copper, Lead and Zinc ions respectively (Technical University of Denmark, 2026).

“Land refill” and “Dock” consists of all processes related to material being reused as land refill, and terracing, as well as redundant material that is planned to be transported to the docks at the site for future usage.

Before any data were gathered or any system boundary and its models were defined, a flowchart were created for each scenario. This was to create an assumed overview over the lifecycle of the soil waste throughout all scenarios, and were a helpful way of understanding and determining the data needed for all processes early on in the study (Baumann & Tillman, 2004, pp. 74–76). These flowcharts were constructed using documents provided by Skellefteå municipality and similar case studies, which determined the Background and Foreground processes within the model, as well as the process input- and output flows and environmental impacts within the system boundary.

3.2.1.3. Scenario 1: Landfilling

As the traditional way of handling large amounts of contaminated soil in Sweden is through excavation and landfill, Scenario 1 consists of said solution. This scenario also includes the base excavation processes, divided into three different excavations: excavation of the 0.4 m depth, excavation and blasting of rock mountains, excavation of other materials (peat, moraine, siporex and sewage sludge) as well as the transportation of external topsoil to the site. After the excavation, the materials are to be reused, either as land refill, noise barrier fill or transported to the docks for future handling. Only the fine fraction in this scenario is considered hazardous and will be transported ex-situ to landfill for further handling, while the rest of the excavated and external material will be reused in-situ.

Scenario 1 consists of all base foreground processes mentioned in Chapter 3.2.1.2 System boundaries and includes transporting the top layer fine fraction waste to Dåva, Umeå. In this scenario, the fine fraction is loaded onto trucks after separation to be transported off the site (Geisler, 2025, p. 27). The remaining coarse fraction waste from excavation will be used as land refill (Geisler, 2025, p. 34). The flowchart for Scenario 1 is shown in Figure 7, which shows the process flow from excavation to immobilization of hazardous fine fraction by landfilling.

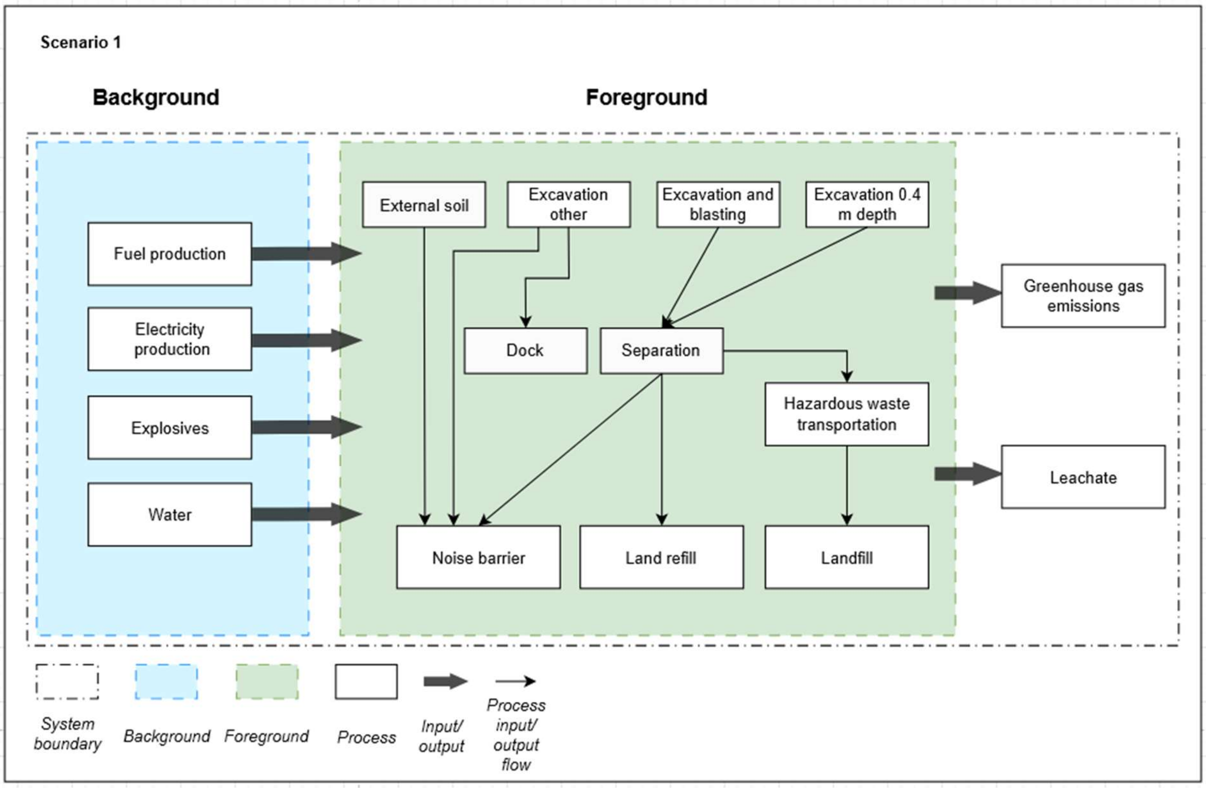

Figure 7: Flowchart of Scenario 1 consisting of System boundary, Background and Foreground processes, and input- and output flows (Geisler, 2025, pp. 34–35; Suer & Andersson-Sköld, 2011, pp. 971–976; Urup Olesen & Damgaard, 2014, p. 3).

After separation, the hazardous fine fraction will be transported with trucks to the Dåva landfill in Umeå, where it is assumed that no pre-treatment will be needed, as leachate tests at Näsudden were performed on a 0-0.5m depth with a Liquid-to-Solid ratio (L/S)=10 limit results below what is considered FA leaching levels. The majority of elevated contamination resides in the 0-0.1 m depth, however, it is assumed that no stabilization will be needed anyway and thus has any pre-treatment processes been excluded (Geisler, 2025, p. 22; Tyréns AB & Skellefteå Kommun, 2017, p. Bilaga 11).

The "Landfill process" includes material fractions and elementary flows needed to operate a landfill, leachate generation and collected- and uncollected leachate (Technical University of Denmark, 2026; Urup Olesen & Damgaard, 2014, p. 4, 2014, pp. 24–39). To disregard capital goods, an operational process were constructed using this base model with data from a case study by Iodice et al. (2021, p. 86, 2021, p. Appendix A.4), where they modelled a landfill in EASETECH for treatment of inert Construction Demolition Waste (CDW) in Italy. This model excluded all capital goods and only included diesel and electricity as external processes.

Landfill leachate occurs when rainwater or snow infiltrates the landfilled soil in combination with compression of the soil. The leachate rate is thus based on the yearly precipitation, how and where the landfill is structured, and the amount of soil that is discarded (Naturvårdsverket, 2008, p. 5). According to measurements at the Bjuröklubb A measure station located to the southeast of Näsudden, the average annual precipitation between 2022-

2024 were 493.9 mm/year (SMHI, 2026), which is considered to be in-between low- to medium precipitation according to the EASETECH leachate generation model (Urup Olesen & Damgaard, 2014, p. 24). It has thus been assumed that, as the precipitation is lingering on the medium precipitation reference value, that the Näsudden area is within the medium limits, and the same precipitation variables have been used for landfilling.

A large part of the Swedish landfills are directing its water to water- or wastewater treatment plants (Naturvårdsverket, 2008, pp. 13–14). Thus the landfill treatment has been modelled using the EASETECH database process Landfill: Leachate - Treatment - Avedoere WWTP, which is based on a simplified model of the Avedoere wastewater treatment plant in Denmark (Technical University of Denmark, 2026). This wastewater treatment plant were modelled to collect 99.9% (0.1% not collected) of the leachate for the first 80 years, and then collect 87% (13% not collected) for the last 20 years (Ferrans et al., 2022, p. 5; Technical University of Denmark, 2019, 2026). The collected and uncollected leachate were only connected to the leachate of As, Cu, Pb and Zn.

The EASETECH modelled Scenario 1 is shown in Figure 8, where smaller processes, such as transportation of soil between processes, have been grouped with their respective main process. A more detailed figure of the Scenario 1 EASETECH model can be found in Appendix 1.

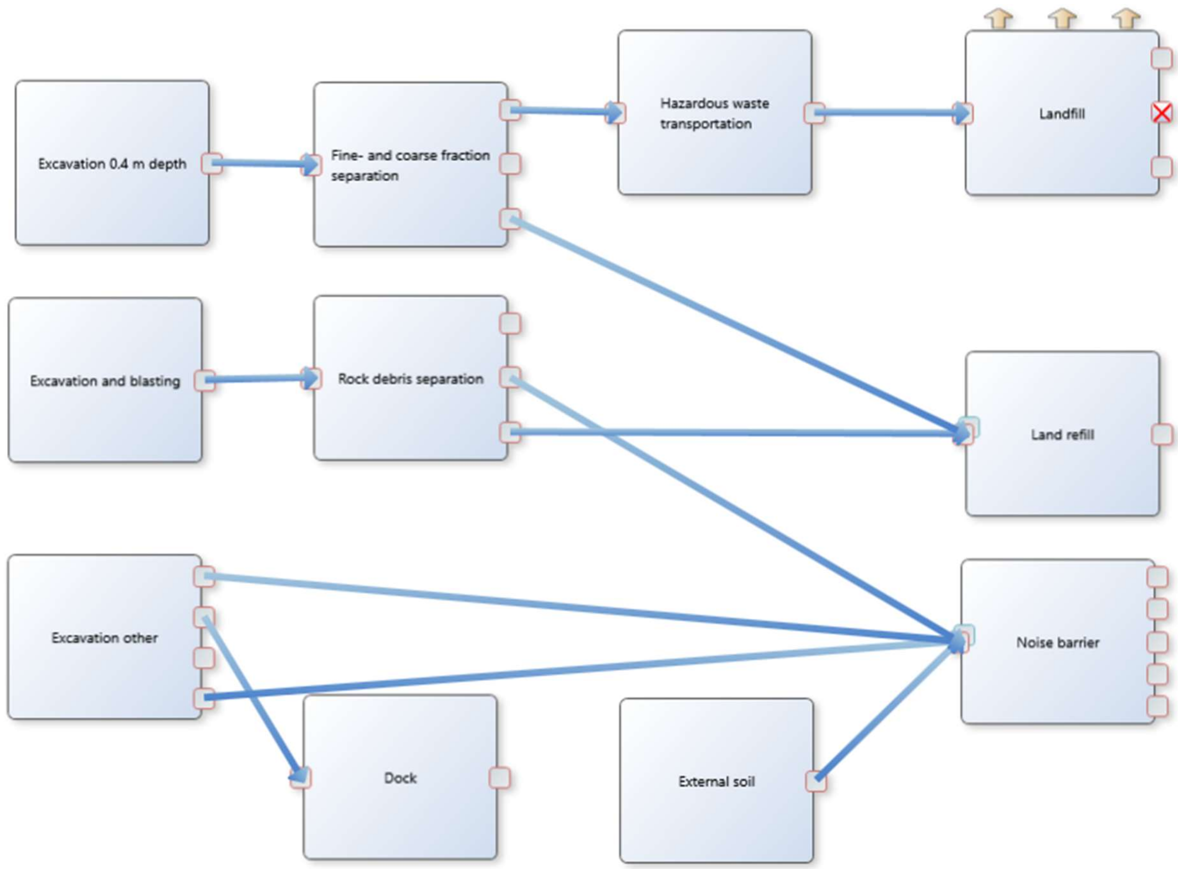

Figure 8: Scenario 1 as modelled in EASETECH with its respective processes and group processes.

3.2.1.4. Scenario 2: Noise barrier encapsulation

In Scenario 2, all the heavy metal contaminated fine fraction soil waste gets encapsulated inside the noise barrier. This excludes all forms of transportation needed ex-situ, and instead the hazardous fine fraction only gets transported in-situ by dumper. This scenario could potentially increase the impacts of leachate from the noise barrier, as all leachate goes uncollected in this scenario.

Scenario 2 consists of the encapsuling the contaminated fine fraction within the noise barrier. By encapsulating the fine fraction inside the noise barrier together with excavated peat, sewage sludge and crushed siporex, and stabilizing it inside the barriers core (Geisler, 2025, p. 43), the process is expected to mixing the hazardous fine fraction soil with the lower contaminated material fraction which could potentially dilute the contaminants and lower the time and costs needed for remediation and handling (Wan et al., 2026, p. 7). This solution would exclude all needs of external transportation of soil waste for deposit. This process flow is shown in Figure 9, where the immobilization of contaminants occurs after the "Noise barrier construction" process, that lies within the "Noise barrier" process.

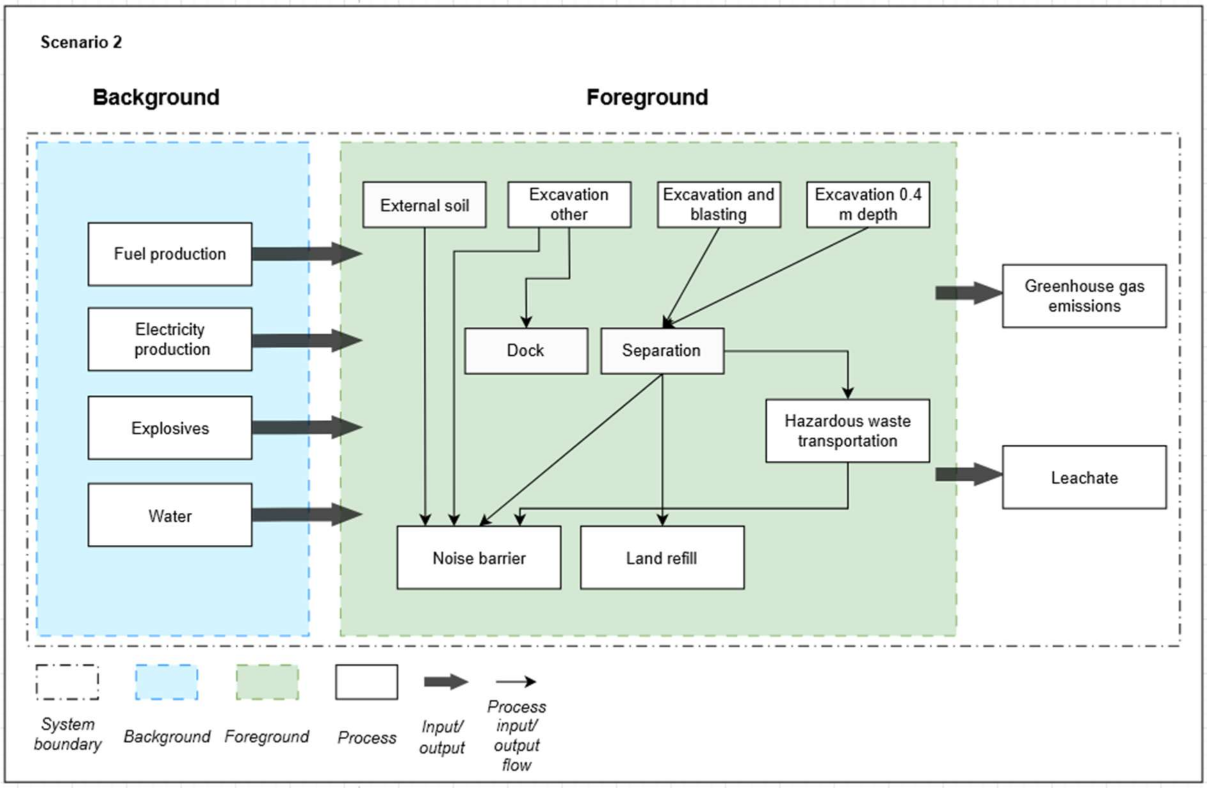

Figure 9: Flowchart of Scenario 2 consisting of System boundary, Background and Foreground processes, and input- and output flows (Geisler, 2025, pp. 34–35; Suer & Andersson-Sköld, 2011, pp. 971–976; Urup Olesen & Damgaard, 2014, p. 3).

The "Noise barrier construction" process for this scenario includes potential leachate generation. Due to the uncertainty of leachate from the noise barrier (Geisler, 2025, p. 40), it is assumed to occur due to the lack of leachate mitigation and the organic structure of the barrier (Geisler, 2025, pp. 40–45). It is also worth noting that mixing the siporex with the contaminated fine fraction could potentially increase the leaching of heavy metals (Vendt &

Paulsson, 2025, p. 23). It is thus assumed that, for the sake of modelling in EASETECH, all material fractions are mixed in the construction of the noise barrier core, where all leachate goes uncollected. Only leachate from As, Cu, Pb and Zn to surface water and attenuation have been considered.

The modelled EASETECH Scenario 2 are shown in Figure 10, which shows the grouped processes and its respective input and output flow. A more detailed figure of the Scenario 2 EASETECH model can be found in Appendix 1.

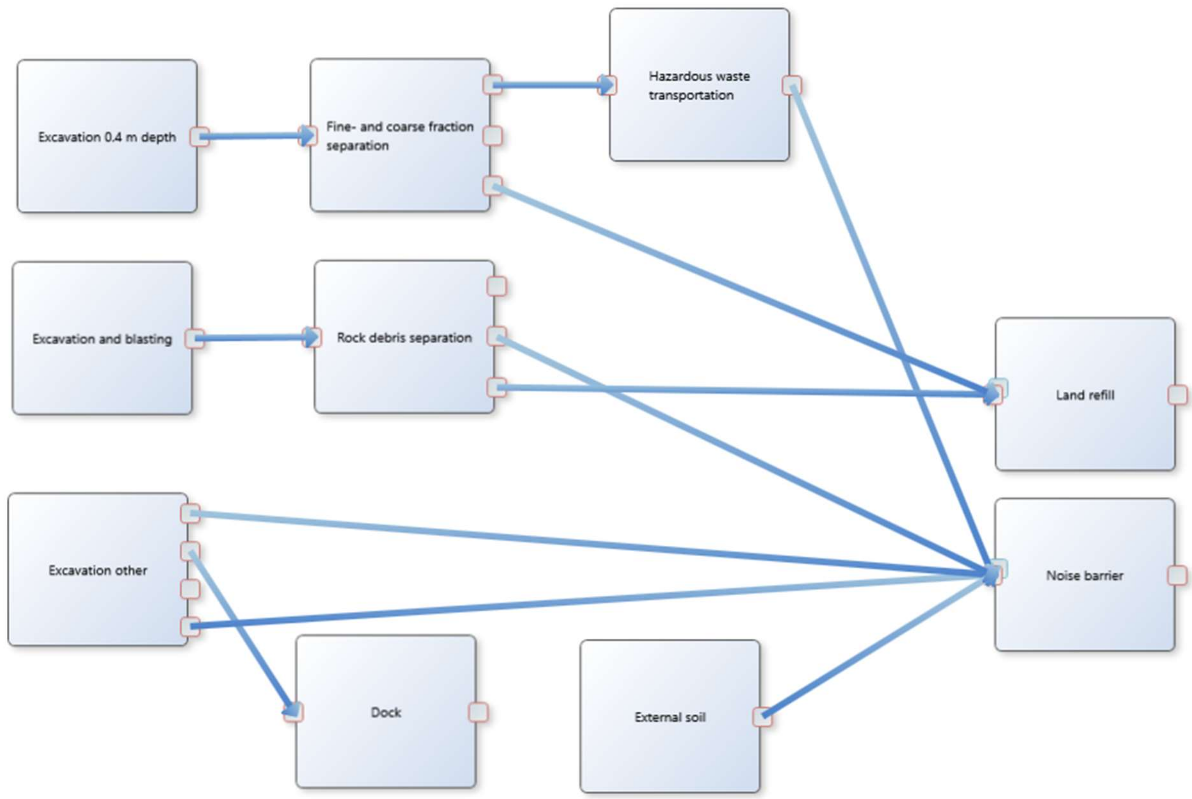

Figure 10: Scenario 2 as modelled in EASETECH with its respective processes and group processes.

3.2.1.5. Scenario 3: Soil wash and Noise barrier encapsulation

Scenario 3 is based on using mobile on-site soil washing to remediate the contaminated fine fraction before reusing it in the noise barrier. This solution is based on the fact that the fine fraction will be cleaned to a certain degree before being encapsulated inside the noise barrier. The final product of the soil washing process is a residual waste product consisting of the contaminants. This residual waste will be considered hazardous, thus classifying as FA and will be deposited as such (Svenska Geotekniska Föreningen, 2026d). Figure 11 shows the flowchart of Scenario 3, where the contaminated hazardous residual waste remaining after the soil washing gets transported for immobilization at landfill.

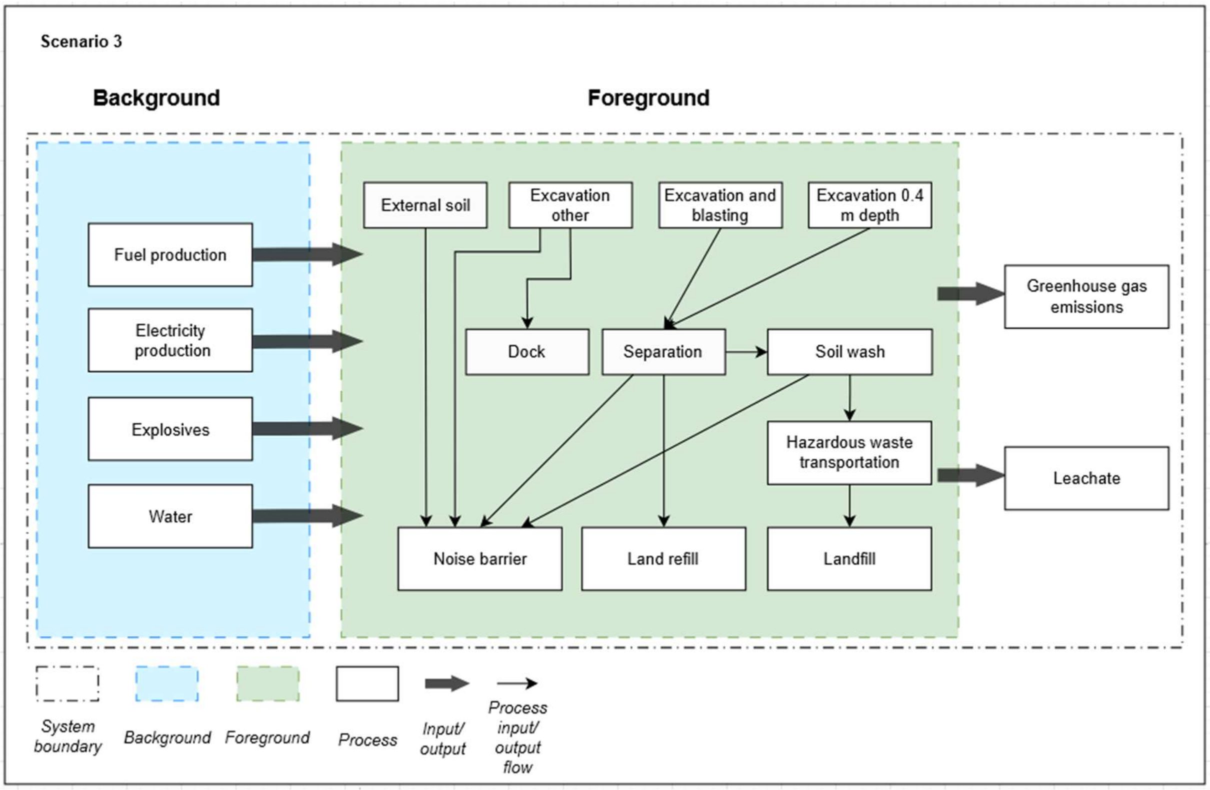

Figure 11: Flowchart of Scenario 3 consisting of System boundary, Background and Foreground processes, and input- and output flows (Geisler, 2025, pp. 34–35; Jia et al., 2026, p. 4; Kostal et al., 2005, p. 521).

No pre-treatment except the base separation process were assumed to take place, and the "Soil wash" process consists of all processes related to soil washing the fine fraction, including separating soil- and liquid, and its summarized electricity and water usage, as well as the removal efficiency of the washing agents (Jia et al., 2026, p. Appendix A; Semer & Reddy, 1996, pp. 46–48). The washer agent used for the model are a 0.6 molar (M) mix of equal parts H_2SO_4 and H_3PO_4, with a L/S ratio of 7:1 and heavy metal removal efficiency of 70-80% (Cho et al., 2020, pp. 7–10),

It was assumed that the wastewater from the soil washing was treated within the process (Ai et al., 2026, pp. 3–5). The remediated soil gets encapsulated inside the noise barrier, thus its organic structure afterwards is deemed unimportant, and the remaining hazardous waste residue after washing, assumed to be around 10-20% of the total fine fraction soil, gets transported for landfilling (Boskalis Environmental, 2023, p. A; Svenska Geotekniska Föreningen, 2026d) which is assumed to be the Dåva landfill in Umeå, where it is handled by the same processes as Scenario 1.

Due to the large area that needs to be treated, it is assumed that the process can be done in smaller areas on different periods. This could be beneficial in a time effectiveness perspective, as it could focus on washing the areas most dire for starting construction. This method also correlates to the need of splitting the excavation up piecewise (Sweco, 2025a, p. 24). For the modelling in EASETECH however, no extra process regarding said patch remediating has been included and is assumed to have minimal impacts on the scenario.

As no processes regarding transportation of machinery to the site have been included for the other scenarios, any impacts of transportation of mobile soil washing machinery to the site have been excluded. It is also thus assumed that the impacts from site preparation and installation are minor in comparison to the impacts of the soil washing process (Vocciante et al., 2021, p. 5). As assumed in Scenario 1, it is expected that the fraction of the fine fraction that gets lost from soil washing has to be replaced using external soil.

Figure 12 shows the EASETECH model for Scenario 3 with all its grouped processes and input and output flows, where the soil washing process consists of the soil washing process as well as the transportation of fine fraction to and from the mobile soil washing station. A more detailed figure of the Scenario 3 EASETECH model can be found in Appendix 1.

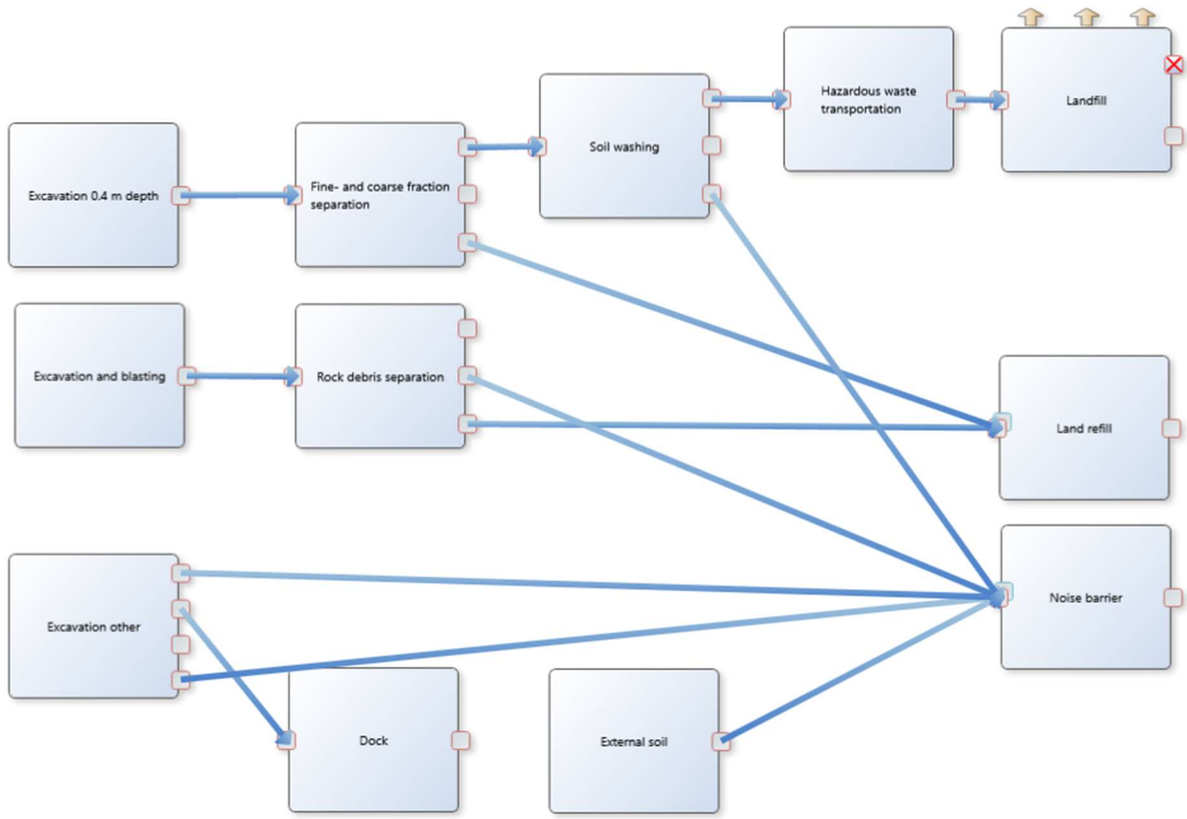

Figure 12: Scenario 3 as modelled in EASETECH with its respective processes and group processes.

3.2.2 Life Cycle Inventory (LCI)

The LCI were conducted using the LCA-software EASETECH developed at the Technical University of Denmark which was provided and recommended by Mälardalen University due to its easy-to-use interface for material flow and environmental impact modelling (Technical University of Denmark, n.d.; H. Tibbetts, personal communication, January 27, 2026).

Primary data were gathered from documents provided by Skellefteå municipality, while secondary data were gathered from similar case studies and service providers, by using English and Swedish keywords such as “soil excavation+machinery”, “lca+soil washing” and "hantering av farligt avfall" using the Google search engine and public research databases such as Google Scholar and Elsevier Scopus.

3.2.2.1. Databases

Secondary data points regarding processes unavailable from in-situ measurements were gathered through LCI databases. The databases used for this study consisted of the Swiss Federal Administration LCI Database BAFU:2025 v2, downloaded from the openLCA Nexus (openLCA, 2025), the EASETECH 2026-01-official database (Technical University of Denmark, 2026) as provided by Mälardalen University (MDU), and the ecoinvent version 3.12 database as provided by MDU.

3.2.2.2. Emission factors

To calculate estimated greenhouse gas emissions in tonnes CO_2-Eq, emission factors were gathered from publicly available databases and similar case studies, as well as Environmental Product Declarations (EPD) from EPD-Global.

3.2.2.3. Amount of soil material

All data variables connected to the amount of soil that is planned to be remediated has been gathered from in-situ measurements, reports and documents provided by Skellefteå municipality. These consisted of measured and calculated data points from Afry, Sweco and Tyréns AB, which had previously been contracted by Skellefteå municipality regarding the Näsudden project (Geisler, 2025, pp. 13–22; Sweco, 2025a, pp. 21–24, 2025b, pp. 5–23; Vendt & Paulsson, 2025, p. 5). The planned to be excavated material were calculated to their respective weight in tonnes according to their density, as shown in Table 6.

Table 6: Total volume, density and weight of all material that is expected and planned to be excavated at Näsudden.

Material	Total volume (m^3)	Density (kg/m^3)	Total weight (tonnes)	Reference(s)
Fine fraction	5.40E+04	1851.85	1.00E+05	(Geisler, 2025, p. 22)
Coarse fraction	2.16E+05	1851.85	4.00E+05	(Geisler, 2025, p. 22)
Rock	1.14E+06	2842.105263	3.24E+06	(Geisler, 2025, p. 22)
Siporex	3.21E+05	600.00	1.92E+05	(Byggbay.se, 2026)
Moraine	2.15E+05	2140.00	4.60E+05	(Svenska Geotekniska Föreningen, 2023a, p. 135)
Sewage sludge	1.55E+04	1022.00	1.58E+04	(Eklund, 1998, p. Bilaga A)
Peat	5.80E+04	300.00	1.74E+04	(Energimyndigheten & Statistiska Centralbyrån, 2002, p. 4)

These material fractions were used to determine the total weight of each excavation process. The excavation processes were divided into three different material generation processes: Excavation 0.4m depth, Rock excavation and blasting and Excavation other, for all scenarios in their respective EASETECH model. These excavation processes, with their respective material fraction percentage, weights and total weights are shown in Table 7.

Table 7: Excavation processes as modelled in EASETECH with their total weight and fraction weights.

Excavation process as modelled in EASETECH	Total weight (kg)	Weight (kg)	Material fraction % of total weight (%)	Material fraction
Excavation 0.4 m depth	5.00E+05	1.00E+05	20.00%	Fine fraction
		4.00E+05	80.00%	Coarse fraction
Rock excavation/blasting	3.24E+06	3.24E+06	100.00%	Rock debris
Excavation, other	6.86E+05	1.92E+05	28.05%	Siporex
		4.60E+05	67.11%	Moraine
		1.58E+04	2.31%	Sewage sludge
		1.74E+04	2.54%	Peat

In EASETECH, the composition of waste, and contaminants per material fraction is determined by the Total Solids (TS). To calculate the weight of the fine fraction and the coarse fraction TS per kg, Equation 1 were used.

$$\text{kgTS} = \%TS_{average} * m_{fraction} \quad \text{Equation 1}$$

Where $m_{fraction}$ (kg) were determined by the total weight of the soil fraction. %TS (%) (in this case the dry matter) were given by the analytic results of X-Ray Fluorescence (XRF) and lab measurements on the area conducted by Afry in 2022, at depths of 0-0.1 m (fine fraction) respectively 0.1-0.4 m (coarse fraction) (Afry, 2022). $\%TS_{average}$ (%) were determined by calculating the average %TS for both fractions respectively.

The water content for each fraction was then determined by Equation 2.

$$\%Water = 100\% - \%TS_{average} \quad \text{Equation 2}$$

The percentage of where each material would end up as refill or filling were determined by weighting each extracted and imported individual material volume with their respective expected volume to be used for the noise barrier and as land refill. Any remaining material were assumed to be transported to the sites docks for future constructing or usage (Geisler, 2025, pp. 20–22 & pp. 43–45; M. Lindmark, personal communication, March 26, 2026). These percentages are shown in Table 8. Any construction or other processes related to said docks were not included in any calculations, except the transportation of excess materials to the area due to limited amount of information and data regarding the process.

Table 8: Total percentage of each material ending up as noise barrier refill, land refill or transported to docks.

Material	To noise barrier refill (%)	To land refill (%)	To docks (%)
Fine fraction	100.0%*	0.0%	0.0%
Coarse fraction	0.0%	100.0%	0.0%
Rock debris	1.9%	98.1%	0.0%
Siporex	20.1%	0.0%	79.9%
Moraine	84.0%	0.0%	16.0%
Sewage sludge	100.0%	0.0%	0.0%
Peat	100.0%	0.0%	0.0%
External topsoil	100.0%	0.0%	0.0%

*Note: * Will only be encapsulated inside noise barrier in Scenario 2 and 3. Will be transported for landfilling in Scenario 1.*

3.2.2.4. Measured levels of contamination

The measured levels of metals and organic contaminants at the site location were provided by Skellefteå municipality. This data has been measured by Thyréns AB and reported in their final result-report Miljöteknisk markundersökning: Resultatrapport Delplan Näsudden. The assignment and report was ordered by Skellefteå municipality 2018-10-24 and included relevant information regarding which contaminants measured were elevated at a toxic level, as well as concentrations of said contaminants in µg/L (Tyréns AB & Skellefteå Kommun, 2017, pp. 1–33). More recent laboratory measures conducted by Afry in 2022 shows similar results, as shown in Table 9, with elevated levels of As, Cu, Pb, Hg and Zn above the Swedish EPA MKM reference values, where As is above the reference levels in both the organic layer and the mineral soil layer measured at 0 to 0.1 m (Geisler, 2025, p. 13; Naturvårdsverket, 2025b, p. 1; Sweco, 2025b, pp. 32–34). All of the contaminants, except Hg are above the Avfall Sverige FA reference levels in the organic layer (Geisler, 2025, p. 13; Sweco, 2025b, pp. 32–34; Tyréns AB & Skellefteå Kommun, 2017, p. Bilaga 10). This layer consists of the fine fraction, that needs to be treated.

Table 9: Summary of laboratory measured levels of contamination in top soil at Näsudden, in comparison to reference values of MKM and FA (Afry, 2022; Geisler, 2025, p. 13; Naturvårdsverket, 2025b, p. 1; Sweco, 2025b, pp. 32–34; Tyréns AB & Skellefteå Kommun, 2017, p. Bilaga 10)

	As	**Cu**	**Pb**	**Hg**	**Zn**
Organic top layer mean 0-0.1m (mg/kg TS)	1781.3	5287.5	10287.5	21.3	2472.5
Mineral soil layer 0.1+ mean (mg/kg TS)	169.8	75.0	72.4	0.1	79.4
Reference MKM (mg/kg TS)	25.0	200.0	180.0	2.5	500.0
Reference FA (mg/kg TS)	1000.0	2500.0	2500.0	1000.0	2500.0

By using Equation 3, the percentage each heavy metal had their fractions TS determined. This were made to be in line with the modelling data input of EASETECH.

$$\%TS_{contaminant} = \frac{m_{contaminant}}{m_{TS}} * 100 \quad \text{Equation 3}$$

Where $m_{contaminant}$ (kg/kg TS) is defined by the weight of the heavy metal, converted from mg/kg TS, and m_{TS} (kg TS) by the total TS weight of the soil.

This were used to determine any missing inputs that were needed to conduct the modelling in EASETECH, such as excavated fine- and coarse fraction amounts of heavy metal contaminants. These calculations were made in Microsoft Excel (Microsoft Corporation, 2026) before importing it into EASETECH.

It is assumed that the 58000m^3 peat that is to be excavated from and outside the northern and southern landfill are as contaminated as the fine fraction according to Geisler (2025, pp. 20–21), and due to limited availability on soil properties and contamination levels in regards to the soil excavated outside the 0.4 m depth area, it has been assumed that the peats contamination levels are at the same percentage (%TS) as the fine fraction, and the other materials (moraine, siporex and sewage sludge) contamination levels are at the same percentage (%TS) as the coarse fraction. After calculating the %TS for each fraction according to Equation 3 and the assumptions made, the results shown in Table 10 were implemented into EASETECH as material fractions.

Table 10: Material fractions and their structure properties imported into EASETECH.

Fraction	***Fine fraction (and Peat)***	***Coarse fraction (and Moraine, Siporex)***	***Sewage sludge***
Water (%)	62.60	13.20	90.00*
TS (%)	37.40	86.80	10.00*
As (%TS)	1.78E-01	1.70E-02	1.70E-02
Ba (%TS)	2.54E-02	3.16E-03	3.16E-03
Cd (%TS)	2.70E-03	1.21E-04	1.21E-04
Co (%TS)	1.07E-03	2.83E-04	2.83E-04
Cu (%TS)	5.29E-01	7.50E-03	7.50E-03
Hg (%TS)	2.13E-03	9.81E-06	9.81E-06
Ni (%TS)	6.91E-03	3.44E-04	3.44E-04
Pb (%TS)	1.03E+00	7.24E-03	7.24E-03
V (%TS)	9.84E-02	2.39E-03	2.39E-03
Zn (%TS)	2.47E-01	7.94E-03	7.94E-03
TOC (%TS)	38.25	1.44	1.44
Reference(s)	(Afry, 2022; Geisler, 2025, pp. 20–22)	(Afry, 2022; Geisler, 2025, p. 22, 2025, p. 14)	(Afry, 2022; Geisler, 2025, p. 22, 2025, p. 14) *(Technical University of Denmark, 2026)

The leaching of As, Cu, Pb and Zn were based on the Analysresultat (Measurement results) Näsudden Dataset conducted at the site by Afry (2022). The mean average leachate concentrates (mg/L) where determined by the lab results from four different measure points of organic top layer and mineral soil layer measurements as shown in Table 11.

Table 11: Mean averages of lab results of leachate concentrates for As, Cu, Pb and Zn in mg/L (Afry, 2022).

	As	**Cu**	**Pb**	**Zn**
Coarse fraction leaching (mg/L)	0.1226	0.0241	0.0072	0.0062
Fine fraction leaching (mg/L)	0.2414	0.2789	0.0773	0.7624

These numbers were used to model the leachate generation within the noise barrier, with a net infiltration of 493.9 mm/year (SMHI, 2026), where it was assumed that no collection would be made, with a waste height layer of 10.4 m, based on the structure of the barrier core (Geisler, 2025, p. 43).

It was assumed that at landfill, leaching collection amounted to 99.9% for the first 80 years, and scaled down to 87% at the last 20 years of a 100 year simulation (Ferrans et al., 2022, p.

6; Technical University of Denmark, 2026), and was based on the EASETECH database process “Leachate - Generation - Medium precipitation area - high substance concentrations”, with a default waste height layer of 10 m and a bulk density of 1.852 tonne/m^3, representing the height layer of compacted waste in a standard landfill (Urup Olesen & Damgaard, 2014, pp. 26–27) and the average density based on the excavated fine- and coarse fraction. It is thus assumed that the hazardous landfilled soil waste gets mixed with other waste types at the landfill, and that the landfill has high substance concentrations due to the hazardous material.

3.2.2.5. Machinery

All machinery needed for the processes are shown in Table 12. These were gathered from an interview meeting with Mikael Lindmark, project manager at Skellefteå Municipality, regarding the machinery that is planned to be used for the project (M. Lindmark, personal communication, March 26, 2026). The table also includes machinery related to soil washing. Assumptions have been made regarding the usage of said machinery to structure the Scenario 1, 2 and 3 models in EASETECH. As exact machinery data were limited before modelling, excavators, bulldozers, wheel loaders, drill rigs and trucks have been estimated using the EASETECH 2026-01-official Database (Technical University of Denmark, 2019).

Table 12: Machinery planned and assumed to be used for each separate process.

Process	Machinery	Comment(s)	Scenario(s)
Excavation	Excavator Bulldozer Wheel loader	Excavator for excavating soil at 0.4m depth. Bulldozer and wheel loader to move and load excavated soil for transportation.	S1, S2, S3
Blasting	Slurry explosives transported by tanker Drill rig Bulldozer Wheel loader	Drill rig used for injection of slurry. Tovex T assumed as water based slurry explosive commonly used for borehole blasting after drill rig usage (SSE Holding SA / SSE & The Norwegian EPD Foundation, 2022, pp. 1–8; SSE Sverige AB, n.d., pp. 1–2). 0.37 kg Tovex T per tonnes of hard rock (De Bortoli, 2023, p. 7). Bulldozer and wheel loader to move and load blasted rock debris for transportation.	S1, S2, S3
In-situ soil transportation	Dumper A30-A40	Dumper transporting soil to other processes	S1, S2, S3
Soil separation	RM HS5000M Cummins Stage5 Wheel loader	3 separators, whereas 2 are running at the same time	S1, S2, S3
Rock debris separation	Bulldozer Wheel loader	Bulldozer and wheel loader to move and load excavated soil for transportation	S1, S2, S3
Crushing	Excavator	Rock debris does not need crushing before reusing. Only siphorex needs crushing before refill, done by crushing with excavator.	S1, S2, S3
Ex-situ soil transportation	Truck 30t-50t	Truck used to transport hazardous soil waste to Dåva, Umeå Truck used to transport external topsoil from Luleå to Näsudden.	S1, S2, S3
Soil washing	Excavator Wheel loader Mobile soil washing unit	Excavator and wheel loader used to load separated fine fraction soil into mobile soil washing unit. Mobile soil washing unit used to wash contaminated fine fraction soil.	S3

All machinery inputs were determined by its fuel consumption in L/kg Total Wet Weight, except for Ex-situ soil transportation, which was determined by kg*km/kg Total Wet Weight for a one-way transportation. The other machineries fuel consumption in L/kg were calculated based on data from similar case studies, estimates and assumptions. The resulting fuel consumptions, and assumptions made for each machinery are shown in Table 13 with their corresponding scenario occurrence. The processes and equations used to calculate these fuel consumption parameters can be found in Appendix 2.

Table 13: Assumptions and fuel consumptions for machinery used in all scenarios.

Process	Assumption(s)	Fuel consumption	Scenario(s)
Excavator	Excavator: Skid steer, combustion 1L of diesel, 2008/2011, 104kW, 31% load factor. (Göteborgs stad, 2025; Technical University of Denmark, 2026).	0.00010260 L/kg (Geisler, 2025, p. 22; Göteborgs stad, 2025; Trafikverket & Skanska, 2025)	S1, S2, S3
Dumper	Dumpers, combustion 1L of diesel, 2008/2011, 153 kW, 33% load factor (Technical University of Denmark, 2026; Trafikverket & Skanska, 2025)	0.00005332 L/kg (Geisler, 2025, p. 22; Göteborgs stad, 2025; Trafikverket & Skanska, 2025)	S1, S2, S3
Drill rig	Drill rig: Combustion of 1L diesel, 2008/2011, 94kW, 33% load factor rate based on hard rock conditions (Göteborgs stad, 2025; Technical University of Denmark, 2026).	0.00002625 L/kg (Göteborgs stad, 2025; Sweco, 2025a, pp. 21–22; Trafikverket & Skanska, 2025)	S1, S2, S3
Wheel loader	Wheel loader: Combustion 1L of diesel, 2008/2011, 94kW, 33% load factor. Small size(Technical University of Denmark, 2026; Trani et al., 2016, p. 3807) .	0.00002160 L/kg (Geisler, 2025, p. 22; Trani et al., 2016, p. 3807)	S1, S2, S3
Bulldozer	Bulldozer: Combustion 1L of diesel, 2008/2011, 112kW, 40% load factor. Assumed U-blade for moving large quantities of soil between points (Diachenko & Balaka, 2025, p. 64; Technical University of Denmark, 2026).	0.00003375 L/kg (Diachenko & Balaka, 2025, p. 64; Geisler, 2025, p. 22)	S1, S2, S3
Separator	330 tonnes/hour treated per separator. Assumed treating efficiency of 660 tonnes/hour at all times (Representative RUBBLE MASTER HMH GmbH, personal communication, April 7, 2026; RM Group, n.d., p. 9)	0.00001515 L/kg (Representative RUBBLE MASTER HMH GmbH, personal communication, April 7, 2026; RM Group, n.d., p. 9; Sweco, 2025a, p. 23)	S1, S2, S3
Truck	Truck, 28t-32t, Euro 6, highway used (Technical University of Denmark, 2026).	120 km (Näsudden-Dåva, Umeå) (Geisler, 2025, p. 14, 2025, p. 24). 140 km (Luleå-Näsudden) (Google, 2026; M. Lindmark, personal communication, March 26, 2026)	S1, S2, S3

3.2.2.6. Soil washing processes

To model the soil washing process for Scenario 3 in EASETECH, the inputs consisting of electricity, water and washing agents had to be converted to input per kg Total Wet Weight respectively (Technical University of Denmark, 2019). Electricity and water were converted to kWh/kg and L/kg (kg/kg) based on the density of the fine- and coarse fraction soil.

Molarity (M) is defined by Equation 4 (Florida State University, n.d.).

$$M = \frac{mol}{V} \qquad \text{Equation 4}$$

Where mol is defined as the moles of solute (mol), and V by the volume solution (L). M is defined as 0.6M or 0.6 mol/L for both H_2SO_4 and H_3PO_4 (Cho et al., 2020, pp. 7–10; Florida State University, n.d.; Tocris Bioscience, 2026).

The $Mass\ of\ solute$ (kg/kg Total Wet Weight) where calculated using Equation 5.

$$Mass\ of\ solute = M * V * Molar\ mass \qquad \text{Equation 5}$$

Where M where defined as 0.6 mol/L for both solutes, V by volume of the solute, calculated by converting the L/S ratio of 7:1 (Cho et al., 2020, pp. 7–10) to 7 L/kg, and $Molar\ mass$ by the molar mass of H_2SO_4 and H_3PO_4 (kg/mol) (National Center for Biotechnology Information, 2025a, 2025b). After the weight of washing agents were calculated, they were unfortunately excluded from the LCA modelling, due to a failing compatibility between gathered ecoinvent data and the EASETECH software. The impacts of the production and usage of washing agents were thus excluded from the end results related to Scenario 3, which impacted the overall uncertainty of the system.

The resulting input values that were used for modelling Scenario 3 in EASETECH: electricity, water, H_2SO_4 and H_3PO_4 are shown in Table 14, together with the removal efficiency of the H_2SO_4 and H_3PO_4 mix and an approximated ratio of remediated clean soil and hazardous waste material.

Table 14: Values for all variables used in the soil washing process.

Input	Data value	Unit	Reference(s)
Electricity	3.5E-03	kWh/kg	(Geisler, 2025, p. 22; Vocciante et al., 2021, p. 5)
Water	6.2	L/kg	
H2SO4 and H3PO4, As removal efficiency (0.6M)	70.5	%	(Cho et al., 2020, p. 9)
H2SO4 and H3PO4, Cu removal efficiency (0.6M)	79.7	%	
H2SO4 and H3PO4, Pb removal efficiency (0.6M)	80.1	%	
H2SO4 and H3PO4, Zn removal efficiency (0.6M)	71.2	%	
Resulting clean soil	80.0-90.0	%	(Boskalis Environmental, 2023, p. A)
Resulting hazardous waste	10.0-20.0	%	

3.2.3 Life Cycle Impact Assessment (LCIA)

A common way of modelling environmental impacts in tonnes CO_2-Eq, is by using the robust and commonly used Global Warming Potential (GWP100) method by the Intergovernmental Panel on Climate Change (IPCC) to determine the midpoint climate change impact related to environmental protection over a set period of 100 years (Hauschild et al., 2013, p. 6; Hauschild & Huijbregts, 2015, pp. 8–9). The International Life Cycle Data System (ILCD) Recommended 2013 Prosuit Global LCIA method includes the IPCC2007 GWP100, USEtox for ecotoxicity, and more models to determine climate change, ozone depletion and other impacts related to the human health, natural environment and natural resources areas of protection (Hauschild et al., 2013, pp. 3–6; Technical University of Denmark, 2026). Table 15 showcases the impact categories that are included in the ILCD 2013 Prosuit Global LCIA model used in EASETECH for all scenarios.

Table 15: Impact categories and their related units, which base model-, method- or reference they are based on, and their respective area of protection (Hauschild et al., 2013, pp. 4–6; Technical University of Denmark, 2026).

Impact category	Unit	Based on model, method or reference	Area of protection
Climate change w/o LT; midpoint.	kg CO_2-Eq	GWP100, 100 years of IPCC2007	Human health, Natural environment, Natural resources
Ozone depletion w/o LT, ODP w/o LT	kg CFC-11 eq	Steady-state Ozone depletion potential (ODP) from WMO assessment	Human health, Natural environment, Natural resources
Human toxicity, cancer effects, w/o LT,	CTUh	USEtox	Human health
Human toxicity, non-cancer effects w/o LT,	CTUh	USEtox	Human health
Particulate matter w/o LT, from, PM	kgPM2.5-Eq	Humbert 2009	Human health
Ionising radiation human health w/o LT, IRP100 w/o LT	kBq U235 eq	ReCiPe 1.05 midpoint (H)	Human health
Photochemical ozone formation, human health w/o LT, POCP	kg NMVOC	ReCiPe	Human health, Natural environment
Terrestrial acidification, Accumulated Exceedance	mol H+ eq.	Accumulated exceedance (AE)	Natural environment
Eutrophication Terrestrial, Accumulated Exceedance	mol N eq.	Accumulated exceedance (AE)	Natural environment
Eutrophication Freshwater,	kg P eq.	FEP ReCiPe 1.05 midpoint (H)	Natural environment
Eutrophication Marine w/o LT,	kg N eq.	ReCiPe2008 1.05	Natural environment
Ecotoxicity freshwater w/o LT,	CTUe	USEtox	Natural environment
Depletion of abiotic resources, mineral fossil & renewable	kg Sb eq.	CML 2002	Natural environment, Natural resources

By focusing on the goal and scope of the study, the municipality sustainability goals, the stakeholders best interest, and to cover all the impacts within each scenarios system

(European Commission, 2010, pp. 367–368; Hillege, 2019), the relevant impact categories, commonly used in soil remediation LCA studies, for researching global environmental impacts and local environmental, health and soil impacts, shown in Table 16 were included, and the non-relevant were excluded from the study (Ding et al., 2024, p. 18; European Commission, 2010, p. 12; Lemming et al., 2010, pp. 120–121) resulting in the chosen impact categories shown in Table 16. Both the impact categories Climate change and Ecotoxicity freshwater were deemed the most important due to its environmental impact from the systems and noise barrier leachate of heavy metals affecting the area and the marine environment outside of Näsudden. The same conclusion, regarding the properties of the area and the marine and land environment, as well as the negative impacts on habitats, soil and the ecosystem, were taken for the inclusion of Eutrophication freshwater, marine, terrestrial, and terrestrial acidification. Due to the human health impacts of the project, and the risks of handling large amounts of heavy metal contaminated soil at the area, connected with the municipality sustainability goals of safe working environments, the effects on Human toxicity, and Particulate matter were included. Ozone depletion were included due to the potential environmental impact a large-scale operation could have on the stratospheric ozone layer (Hillege, 2019).

Table 16: Chosen impact categories for the case study based on their relevance in the study.

Impact category	Relevancy in study
Climate change	Goal and scope Municipality sustainability goals Stakeholders best interest Environmental impact Human health impact
Ozone depletion	Environmental impact Human health impact
Human toxicity, cancer effects	Goal and scope Municipality sustainability goals Human health impact
Human toxicity, non-cancer effects	Goal and scope Goal and scope Municipality sustainability goals Human health impact
Particulate matter	Goal and scope Human health impact
Terrestrial acidification, Accumulated Exceedance	Goal and scope Environmental impact
Eutrophication Terrestrial, Accumulated Exceedance	Goal and scope Environmental impact
Eutrophication Freshwater,	Goal and scope Environmental impact
Eutrophication Marine	Goal and scope Environmental impact
Ecotoxicity freshwater	Goal and scope Stakeholders best interest Environmental impact

3.2.4 Interpretation

The interpretation of the results was conducted during the LCI, LCIA and after all modelling had been finalized. This interpretation included performing sensitivity and uncertainty analytics, as well as interpreting and discussing the results and its limitations.

3.2.4.1. Data quality analysis

The data gathered for all modules within the system boundaries for each scenario were rated according to the pedigree matrix based on the "Data quality guideline for the ecoinvent database version 3" and the International Reference Life Cycle Data System (ILCD) handbook by the European Commission, in order to keep track of uncertainties and assumptions within data points and value its quality. This model rates the data in a scale of 1-5, where 1 consists of very good quality data, and 5 consists of very poor-quality data, with indicator scores related to Technological representativeness (TeR), Geographical representativeness (GR), Time-related representativeness (TiR), Completeness (C) and Reliability (Precision uncertainty) (P). If a data variable is rated as 0, it is deemed non-applicable (European Commission, 2010, pp. 329–333; Weidema et al., 2013, p. 76). A Data Quality Rating (DQR) is then calculated based on these parameters to determine the overall quality of the data variable using Equation 6.

$$DQR = \frac{TeR + GR + TiR + C + P + X_w * 4}{i + 4}$$ Equation 6

Where X_w is defined by the weakest quality level obtained of the parameters and i is defined by number of applicable data quality indicators. A parameter with a DQR result of ≤1.6 is considered high quality, >1.6 to ≤3 basic quality, and >3 as low quality or estimated data (European Commission, 2010, p. 332).

Too keep track on the data variables for further quality assurance and to justify any uncertainties or assumptions, notes of Time period, Date added, Reference(s), Comments and defining the data variables as Primary or Secondary were made.

All data variables and the pedigree matrix can be found in Appendix 3.

3.2.4.2. Contribution analysis

A contribution analysis were conducted to analyse the hotspot processes with the major impacts according to Skellefteå municipalities most important impact categories (European Commission, 2010, p. 26, 2010, pp. 136–137). As climate change were deemed as an important impact of the scenarios modelled, the impact category Climate change GWP100; IPPC2007 (kg CO_2-Eq) were chosen to determine the key climate change impacts of the system. Another important aspect of the study were the impacts of leachate in the system, and due to the shallow groundwater sources and marinal connection to the Gulf of Bothnia, the impact category Ecotoxicity freshwater in Comparative Toxic Unit for Ecosystems (CTUe) where used to recognize its hotspot processes (European Commission, 2010, pp. 136–137).

3.2.4.3. Sensitivity analysis

After the contribution analysis were made for all scenarios regarding the impact categories Climate change GWP100; IPPC2007 (kg CO_2-Eq) and Ecotoxicity freshwater (CTUe) a perturbation analysis was chosen as the method used to conduct the sensitivity analysis. This method is used to map the processes parameter uncertainties related to the contribution analysis results (Clavreul et al., 2012, p. 2486) and were done in the EASETECH software using the Perturbation Analysis (PA) function with a PA value of 1.1 to determine the relative change of the scenarios result in terms of relative change in a parameter as calculated by the Sensitivity Ratio (SR) in Equation 7 when the process parameters gets increased by 10% (Clavreul et al., 2012, p. 2418; Ferrans et al., 2022, p. 7; Technical University of Denmark, 2019).

$$SR = \frac{\frac{\Delta Results}{Initial\ results}}{\frac{\Delta Parameter}{Initial\ parameter}}$$

Equation 7

3.2.4.4. Uncertainty propagation: Monte Carlo

The results from the perturbation analysis with a SR result above 0.05 which were deemed as having a higher uncertainty and a higher probability of impacting the results were investigated further using a Monte Carlo simulation with 10000 iterations as proposed by Clavreul et al. (2012, pp. 2491–2493). Using Monte Carlo simulations to conduct the uncertainty propagation is a common and trusted method, which can be done directly in EASETECH (Clavreul et al., 2012, p. 2486; Technical University of Denmark, 2019).

The parameters used where either specific to a scenario or all scenarios and were set in EASETECH with sensitivity analysis variables according to normal distribution (ND). This was done in preparation for doing the Monte Carlo simulation, as ND for parameters has a direct iteration with the simulation in EASETECH (Department of Environmental Engineering Technical University of Denmark, 2021, pp. 37–38).
The parameters where determined by input default value, and SA values using the string ND(average,deviation), where average was determined by the sample mean, and deviation by the sample standard deviation calculated by using Equation 8 in Microsoft Excel (Department of Environmental Engineering Technical University of Denmark, 2021, pp. 37–38; Devore, 2012, p. 36; Microsoft Corporation, 2026).

$$s = \sqrt{\frac{\sum (x_i - \bar{x})^2}{n - 1}}$$

Equation 8

Where x_i is defined by each separate measured data variables, $\bar{x}$ by the sample mean and n by the number of data variables.

This equation was used to calculate the standard deviation of parameters with access to more than one measured data variable, particularly the leaching properties of the soil fractions. For the parameters without primary data availability, an average uncertainty of 20% were used, based on the assumption made by Iodice et al. (2021) from which a majority of the parameters related to the landfilling process where gathered. These input parameters, including their respective standard deviation and SA values imported into EASETECH are shown in Table 17. By importing them into the parameter table in EASETECH, the reusability between the scenarios and the project increases the automation of the system and the Monte Carlo simulations.

Table 17: Default values, mean values, standard deviations and EASETECH SA values for all data parameters imported into EASETECH to conduct the Monte Carlo simulations (Afry, 2022).

Parameter	Input	s	EASETECH input
As leachate (>MKM<FA)	1.23E-01	6.39E-02	ND(1.23E-01, 6.39E-02)
As leachate (>FA)	2.41E-01	1.73E-01	ND(2.41E-01, 1.73E-01)
Bulldozer, combustion 1L of diesel, 2008/2011	3.38E-05	6.75E-06	ND(3.38E-05, 6.75E-06)
Clean soil % after soil wash	8.50E+01	1.70E+01	ND(8.50E+01, 1.70E+01)
Cu leachate (>MKM<FA)	2.41E-02	2.33E-02	ND(2.41E-02, 2.33E-02)
Cu leachate (>FA)	2.79E-01	1.23E-01	ND(2.79E-01, 1.23E-01)
Diesel mix, production mix, 2008, EU-27, ELCD	1.71E-02	3.42E-03	ND(1.71E-02, 3.42E-03)
Dumpers, combustion 1L of diesel, 2008/2011	5.33E-05	1.07E-05	ND(5.33E-05, 1.07E-05)
Excavated material, 0.4 m depth (climate change)	5.00E+03	1.00E+03	ND(5.00E+03, 1.00E+03)
Excavated material, 0.4 m depth (ecotoxicity freshwater)	5.00E+03	1.00E+03	ND(5.00E+03, 1.00E+03)
Excavator, skid steer, combustion 1L of diesel, 2008/2011	1.03E-04	2.05E-05	ND(1.03E-04, 2.05E-05)
External soil	1.40E+03	2.80E+02	ND(1.40E+03, 2.80E+02)
Hazardous waste material % after soil wash	1.50E+01	3.00E+00	ND(11.50E+01, 3.00E+00)
Rock debris (climate change)	3.24E+04	6.48E+03	ND(3.24E+04, 6.48E+03)
Rock debris (ecotoxicity freshwater)	3.24E+04	6.48E+03	ND(3.24E+04, 6.48E+03)
Truck, 28t-32t, Euro6, highway (external soil)	1.40E+02	2.80E+01	ND(1.40E+02, 2.80E+01)
Truck, 28t-32t, Euro6, highway (landfill)	1.20E+02	2.40E+01	ND(1.20E+02, 2.40E+01)
Wheel loader, combustion 1L of diesel, 2008/2011	2.16E-05	4.32E-06	ND(2.16E-05, 4.32E-06)
Zn leachate (>FA)	7.62E-01	7.90E-01	ND(7.62E-01, 7.90E-01)

The Monte Carlo results for the impact categories Climate change GWP100; IPPC2007 (kg CO_2-Eq) and Ecotoxicity freshwater (CTUe), being the same impact categories used for the perturbation analysis, in EASETECH provided mean value, distribution and variance, as well as relative frequency for each scenario (Technical University of Denmark, 2019). These results were imported into Microsoft Excel to create comparison histograms using the Analytisis ToolPak Add-in (Microsoft Corporation, 2026).

3.2.4.5. *Uncertainty propagation: Discernability analysis*

A discernability analysis were conducted in order to evaluate the uncertainty propagation results from the Monte Carlo simulations between the scenarios. This method is used to evaluate the difference in mean- and standard deviation results from the Monte Carlo simulations between the scenarios (Clavreul et al., 2012, pp. 2487–2491).

The chosen method of calculating and displaying the discernability analysis is through determining the percentages where one scenario has a higher Monte Carlo simulation result than the other, (p(A>B)) (%), based on 10000 runs. This were done using Equation 9 using Microsoft Excel (Heijungs & Kleijn, 2001, p. 147; Microsoft Corporation, 2026).

$$p(A > B) = \frac{COUNTIFS(A > B, TRUE)}{n}$$ *Equation 9*

Where COUNTIFS(A>B,TRUE) counts the number of rows where A>B=TRUE, where A>B symbolizes for example Scenario 1>Scenario 2 or Scenario 3>Scenario 1, and n is determined by the number of simulations (10000).

3.3 Economic analysis

To conduct the economic analysis, costs for processes within the LCA, such as transportation of soil waste, waste management, and remediation methods, was gathered in SEK and weighed to include inflation. All cost-related calculations for the economic analysis were made using Microsoft Excel and implemented into EASETECH (Microsoft Corporation, 2026; Technical University of Denmark, 2019). The most common approach when combining an environmental LCA with an LCC is to perform an environmental LCC, which consists of the same FU, "1 tonnes of hazardous fine fraction", within the same system boundaries and aligns with ISO 14040 and 14044 (Rödger et al., 2018, pp. 373–374, 2018, p. 379)

3.3.1 Cost data

Estimated costs for waste management and remediation were gathered from relevant publicly available documents and reports from waste treatment plants, costing proposals from companies relevant within the field, and from similar case studies. Some cost data related to the processes of the scenarios were handled over by Skellefteå municipality. The focus was to gather cost data from waste treatment plants and remediation companies near the site, and in cases of data unavailability, other resources was gathered within Sweden.

3.3.1.1. Temporal distribution

Any gathered cost data with prices from years differing from the reference year of 2026 were adjusted to take inflation into account using Equation 10 (Rödger et al., 2018, p. 377).

$$P(t) = (1 + r)^t * P(0) \quad \text{Equation 10}$$

Where $P(t)$ (SEK) is defined by the cost at time t=2026, r (%) by an inflation rate of 1.6% based on the inflation rate in Sweden in March 2026 (Sveriges Riksbank, 2026), t (years) by the differing years, and $P(0)$ by the reference cost (Rödger et al., 2018, p. 377).

3.3.1.2. Cost data inputs

The data parameters which were gathered and adjusted accordingly were the budget and transfer costs related to the remediation of the FU. The processes and reference flows that were static within the system across all scenarios were not included. These gathered data costs, and their respective adjusted costs are shown in Table 18, and where imported into their individual scenario in EASETECH using the built in Cost Data function (Technical University of Denmark, 2019). No costs related to environmental or human health impacts were included.

Table 18: Gathered cost data and their respective adjusted costs for each input connected to the FU in the system.

Input	Adjusted cost (SEK/tonne)	Scenario(s)	Comment(s)	Reference(s)
Transportation of fine fraction to noise barrier	4.08	S2, S3	Estimated cost of transportation hazardous fine fraction to noise barrier, converted from SEK/ha to SEK/m3 divided by density of fine fraction. Adjusted cost from 2023 to 2026.	(Geisler, 2025, p. 22; Hansson, 2023, p. 5)
Transportation of hazardous material from Näsudden to Dåva landfill	251.71	S1, S3	Approximated by reference, based on lumpsum of 20 SEK/mile/tonne. Adjusted cost from 2025 to 2026.	(Geisler, 2025, p. 22)
Landfill tax	750.00	S1, S3	Landfill tax at Dåva landfill. Cost from 2026	(Umeå Deponi och Avfallscenter, 2026, p. 1)
Contaminated soil for landfilling >FA	670.00	S1, S3	Cost for landfilling contaminated waste above the FA limits at Dåva landfill. Cost from 2026.	
External soil	546.88	S1, S2, S3	Cost of dressing soil divided by density of matjord. Cost from 2026.	(Norrlandsjord & Miljö AB, 2026b; Snabbgrus, 2026; Y-Kross AB, 2026)
Mobile soil washing	614.64	S3	Upper range cost of mobile soil washing, based on Svevia mobile soil wash. Adjusted cost from 2019 to 2026	(Jansson, 2019, p. 26)

3.4 Summarization of assumptions

Due to the complex nature of the project and the many unknowns related to the research and modelling of the scenarios, assumptions have been made throughout the study. These assumptions were made using sources such as interviews with people connected to or previously connected to the Näsudden project, similar case studies, and information from service providers and manufacturers.

Table 19 shows the assumptions made and what type of impact said assumptions may have on the end results and the process of the study. Assumptions related to data collection have been excluded from the table and are shown through their respective DQR in Appendix 3.

Table 19: Assumptions made in Chapter 3. Method with their respective impacts in the study.

Assumption	**Impacts**
Hazardous material immobilized at landfill in Scenario 1 and Scenario 3, and after encapsulation inside noise barrier in Scenario 2.	Attributional approach. No further processes included after immobilization.
Reference flow parameters and processes assumed to be the same between all scenarios.	All processes and parameters stay the same except the processes and parameters related to the FU. These processes and parameters are included in the end results.
Separated coarse fraction will not be crushed before reuse.	No fuel or energy consumption related to crushing coarse fraction may lower impact end results.
No pre-treatment needed before landfilling hazardous material	No fuel or energy consumption related to treatment may lower impact end results.
Bjuröklubb A average yearly precipitation assumed for both Näsudden and landfill.	May impact end results connected to leachate from noise barrier and landfill.
Leachate collection at landfill: 99.9% first 80 years. *87% last 20 years.*	May impact end results connected to leachate from landfill.
All material fractions get mixed inside the noise barrier.	May impact end results connected to leachate from noise barrier.
Clean soil- and hazardous waste material resulting from soil wash: 85% clean soil. *15% hazardous waste material.*	May impact end results connected to leachate from noise barrier and landfill, and ex-situ transportation.
Transporting mobile soil washing machinery and preparation excluded from model.	May impact end results connected to mobile soil wash.
Peat contamination levels are the same as Fine fraction. *Moraine, Siporex and Sewage sludge contamination levels are the same as Coarse fraction.*	May impact end results connected to leachate from noise barrier.
Noise barrier leachate goes uncollected	May impact end results connected to leachate from noise barrier.
Type of machinery used on site	May impact end results connected to all machinery processes.
Impacts of washing agents excluded.	May impact the end results connected to mobile soil wash.
Average uncertainty of 20% used for all parameters except leachate parameters.	May impact the end results connected to Monte Carlo simulations.
Environmental costs excluded from economic analysis	May impact the end results connected to the economic analysis.

These assumptions, as well as the assumptions made during scenario modelling and data collection in the LCI played a key role in the LCIA, Interpretation and Economic analysis results, as higher usage of assumptions and estimates led to higher uncertainties. They were however beneficial for the study as they opened the possibilities needed to conduct the research and were thus included. The impacts of these uncertainties were investigated further in the Chapters 4.1.3 Interpretation and 5 Discussion.

4 RESULTS

This section shows the results of the LCA and follows the standards of ISO 14040 and 14044. It also includes the results of the economic analysis.

4.1 LCA

This section covers the results from the LCA conducted in EASETECH and Microsoft Excel.

4.1.1 LCIA results

The results from the LCIA done with the ILCD Recommended 2013 Prosuit Global LCIA method in EASETECH are shown in Table 20. This table shows the summarized results for the 10 chosen impact categories related to environmental and human health impacts for Scenario 1: Landfilling, Scenario 2: Noise barrier encapsulation, and Scenario 3: Soil wash and Noise barrier encapsulation are based on the FU of 1 tonne hazardous fine fraction to immobilize contaminants under critical levels. A more detailed table showing the LCIA impact category results per process is shown in Appendix 4.

Table 20: Summarized LCIA results for each impact category for Scenario 1, Scenario 2 and Scenario 3.

Impact category	Scenario 1	Scenario 2	Scenario 3	Unit
Climate change	7.95E+01	5.83E+01	6.25E+01	kg CO_2-Eq
Ozone depletion	3.27E-08	2.20E-08	6.44E-08	kg CFC-11 Eq
Human toxicity, cancer effects	9.73E-07	9.16E-07	9.28E-07	CTUh
Human toxicity, non-cancer effects	9.03E-05	7.70E-05	7.92E-05	CTUh
Particulate matter	1.49E-02	1.01E-02	1.22E-02	kgPM2.5-Eq
Photochemical ozone formation, human health	5.58E-01	4.94E-01	5.09E-01	kg NMVOC
Terrestrial acidification, Accumulated Exceedance	5.22E-01	4.08E-01	4.32E-01	mol H+ eq.
Eutrophication Terrestrial, Accumulated Exceedance	2.39	2.10	2.16	mol N eq.
Eutrophication Freshwater	1.16E-04	4.87E-05	6.73E-05	kg P eq.
Eutrophication Marine	2.11E-01	1.88E-01	1.94E-01	kg N eq.
Ecotoxicity freshwater	2.21E+02	2.54E+02	2.49E+02	CTUe

Scenario 1 has the higher impact on climate change, with 79.5 kg CO_2-Eq, compared to 58.3 kg CO_2-Eq in Scenario 2, and 62.5 kg CO_2-Eq. in Scenario 3. This relates to the fact that all three scenarios have high impacts related to the excavation and blasting of rock mountains at the area, which results in high amounts of heavy rock debris that will be reused as land refill. Scenario 1 also experiences higher climate impacts related to handling the fine fraction, as a higher amount of hazardous fine fraction needing to be landfilled increases the climate impact from ex-situ transportation, operation of the landfill, and leachate treatment at the landfill. Due to a larger amount of hazardous material that needs to be transported from the site in Scenario 1 than Scenario 2, and Scenario 3, the climate impacts from transporting external soil to the site increases as a larger amount of replacement soil is needed. Ozone depletion is the highest in Scenario 3, at 6.44E-08 kg CFC-11 Eq, mainly due to the impact of the soil washing, where electricity usage has the highest impact in the process.

The toxic impact on humans is higher for non-cancer effects than cancer effects, with all scenarios end results being relatively close to each other, yet Scenario 1 has the highest impact on human toxicity overall at 9.73E-07 Comparative Toxic Unit for Humans (CTUh), respectively 9.03E-05 CTUh for cancerous and non-cancerous effects. The main reason behind the elevated human toxicity impact is from the leachate of As, Cu, Pb and Zn, mainly from the leachate that goes uncollected from the noise barrier. The effect from said leachate gets lower at Scenario 3, but the leachate that gets generated at the landfill increases the human toxicity impacts overall for the scenario.

The impacts from particulate matter are elevated in Scenario 1 at 1.49E-02, in comparison to Scenario 2 and Scenario 3, mainly due to the diesel and electricity needed to handle the large amount of landfilled fine fraction. This process gets completely removed from Scenario 2 and gets lower in Scenario 3 due to the lower amount of hazardous waste material needing to be landfilled.

The processes with the highest impact on terrestrial acidification are related to the excavation and blasting of rock mountains, with approximately 0.15 mol H+ eq. and 0.11 mol H+ eq. for excavation and blasting using machinery and explosives, and land refill with said rock debris. However, Scenario 1 has a slightly higher terrestrial acidification impact at 0.522 mol H+ eq. compared to the other scenarios due to a higher amount of hazardous waste material that needs to be handled at the landfill.

Scenario 1 also has the highest results for all eutrophication impact categories at 2.39 mol N eq., 1.16E-04 kg P eq., and 2.11E-01 kg N eq. for terrestrial, freshwater and marinal eutrophication respectively. For this case, all processes related to the excavation and blasting of rock mountains have the highest impact in relation to terrestrial and marinal eutrophication across all scenarios. These processes include excavation and blasting with machinery and explosives, land refill, separation and transportation of rock debris to the land refill. Scenario 1 has, however, a higher result than Scenario 2 and Scenario 3 due to the larger amount of hazardous waste material that needs to be handled at the landfill. The diesel and electricity needed to handle this amount plays a particular part in the elevated amount of freshwater eutrophication compared to Scenario 2 and Scenario 3.

The highest impact on ecotoxicity in freshwater sources happens in Scenario 2. Where a higher amount of heavy metal contaminated fine fraction that gets encapsulated inside the noise barrier without any collection of hazardous leachate gives the scenario an impact result of 2.54E+02 CTUe. This uncollected leachate from noise barrier material above FA reference levels accounts for approximately 64.7% of the total impact. However, in Scenario 3, the uncollected leachate from noise barrier material above FA reference levels still plays a big role in the impact result of the scenario, as although the fine fraction is cleaned to As, Cu, Pb and Zn levels below the FA reference levels, the remaining amount of heavy metals are still higher than the MKM levels. Another parameter related to the increased ecotoxicity from uncollected leachate are the fact that the materials included in the noise barrier construction (except the external soil) are assumed to have As, Cu, Pb and Zn levels either above MKM, but below FA reference levels (moraine, siporex, and sewage sludge), or above FA reference levels (peat). Figure 13 shows the results from Table 20 separated into each separate impact category, to show the comparison between the three scenarios graphically.

Figure 13: LCIA results for the chosen impact categories for Scenario 1, Scenario 2, and Scenario 3, for each separate impact category.

4.1.2 Noise barrier impacts

Figure 14 shows the total Ecotoxicity freshwater impact from all three scenarios divided into the noise barrier with the highest impact versus all other processes in their respective system. This shows that a significant amount of freshwater ecotoxicity impact comes from the uncollected leachate of the encapsulated material that have heavy metal contamination levels over the FA reference levels. In Scenario 1, the only uncollected leachate from material above FA comes from the encapsulated peat, whereas in Scenario 2 and Scenario 3 the uncollected leachate above FA consists of the encapsulated peat and the hazardous fine fraction. This uncollected leachate amounts to approximately 64.7% of the total freshwater ecotoxicity of the system in Scenario 2, in comparison to the encapsulated peat resulting in 11.0% of the total freshwater ecotoxicity of the system in Scenario 1. We can also see that the same uncollected leachate has a high impact in Scenario 3, even after being washed in the mobile soil washing unit.

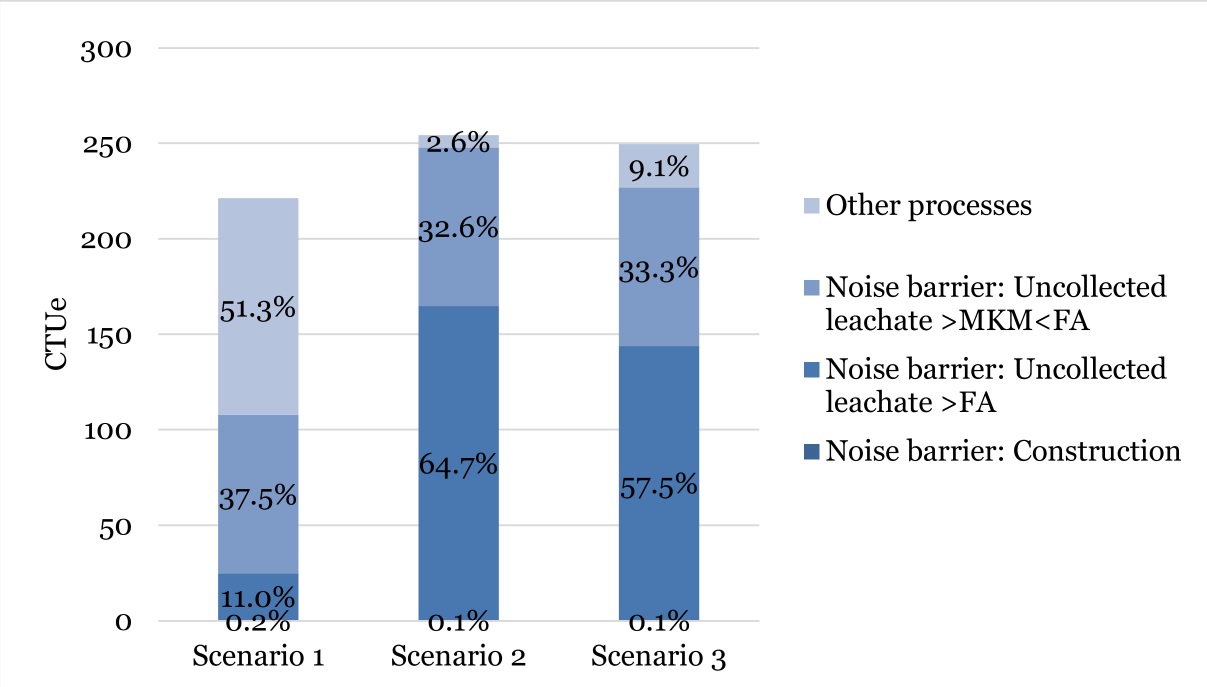

Figure 14: Total ecotoxicity freshwater impact for Scenario 1, Scenario 2, and Scenario 3, showing noise barrier processes weighed against other processes.

This high amount of impact in Scenario 3 is however highly uncertain, as the same leachate parameters have been used across all scenarios. The resulting levels of heavy metals in the fine fraction after the soil washing process with H_2SO_4 and H_3PO_4 removal efficiencies of 70.5%, 79.7%, 80.1%, and 71.2% for As, Cu, Pb and Zn respectively (Cho et al., 2020, p. 9), is shown in Table 21. This table shows that all heavy metal levels have been reduced below FA reference levels, yet they are all higher than MKM reference levels. The leachate and resulting heavy metal parameters play a key role in the uncollected leachate above FA reference levels related to the washed fine fraction.

Table 21: Heavy metal levels after mobile soil washing process in Scenario 3, showcasing the levels before and after soil wash, MKM reference levels and FA reference levels.

	As	Cu	Pb	Zn
Fine fraction before soil wash (mg/kg TS)	1781	5288	10288	2473
Fine fraction after soil wash (mg/kg TS)	525	1073	2047	712
Reference MKM (mg/kg TS)	25	200	180	500
Reference FA (mg/kg TS)	1000	2500	2500	2500

For Scenario 2, the uncollected leachate from the encapsulated material above FA reference limits, meaning the peat and untreated fine fraction, were investigated further as shown in Figure 15. This figure shows each heavy metals amount of impact regarding the cancerous- and non-cancerous effects from human toxicity, and freshwater ecotoxicity impact categories. As has the highest impact of the heavy metals in human toxicity related to cancerous effects, where it amounts to approximately 99.7% of the impact. As also has the highest impact related to non-cancerous human toxicity, and accounts for approximately 87% while Pb accounts for around 12.88%. Pb however, has the highest impact related to freshwater ecotoxicity, where it accounts for approximately 53.87%. In comparison, Cu and As accounts for approximately 28.22% respectively 17.86%, and Zn has the lowest overall impact across all three impact categories.

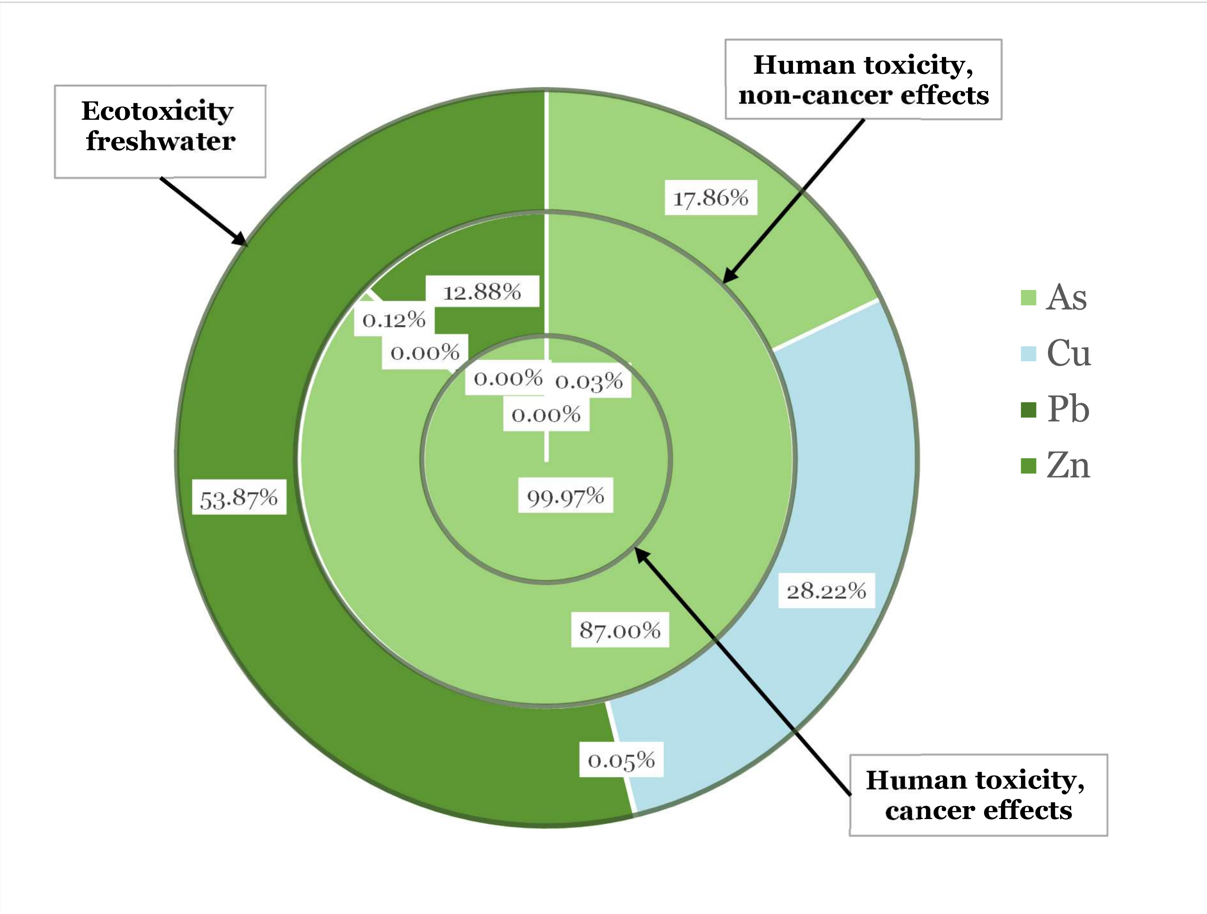

Figure 15: Each heavy metals impact from the uncollected leachate above FA reference levels from the noise barrier in Scenario 2.

4.1.3 *Interpretation*

This section covers the interpretation results from the contribution analysis, sensitivity analysis, data quality analysis, uncertainty propagation and discernibility analysis to showcase the stability and uncertainties of the models.

4.1.3.1. Contribution analysis

The contribution analysis, or hotspot analysis results regarding the impact category Climate change (kg CO_2-Eq) according to GWP100 and IPCC2007 are shown in Figure 16, where the highest impact for all three scenarios comes from Refilling excavated land at site (21.3% in Scenario 1 29.3% in Scenario 2, and 27.3% in Scenario 3), and Excavation and blasting (20.5% in Scenario 1, 28.2% in Scenario 2, and 26.3% in Scenario 3) in comparison to the total amount of kg CO_2-Eq for all models. These results are due to the high amount of excavated and blasted rock mountains at the area which amounts to approximately 3240000 tonnes, or 1200000 m^3 rock mountains and debris which will be reused as part of the land refilling process (Sweco, 2025a, pp. 21–22). This also results in high impact from the process of Rock debris separation, and transportation to land refill across all scenarios (6.8% and 6.4% in Scenario 1, 9.3% and 8.8% in Scenario 2, and 8.7% and 8.2% in Scenario 3).

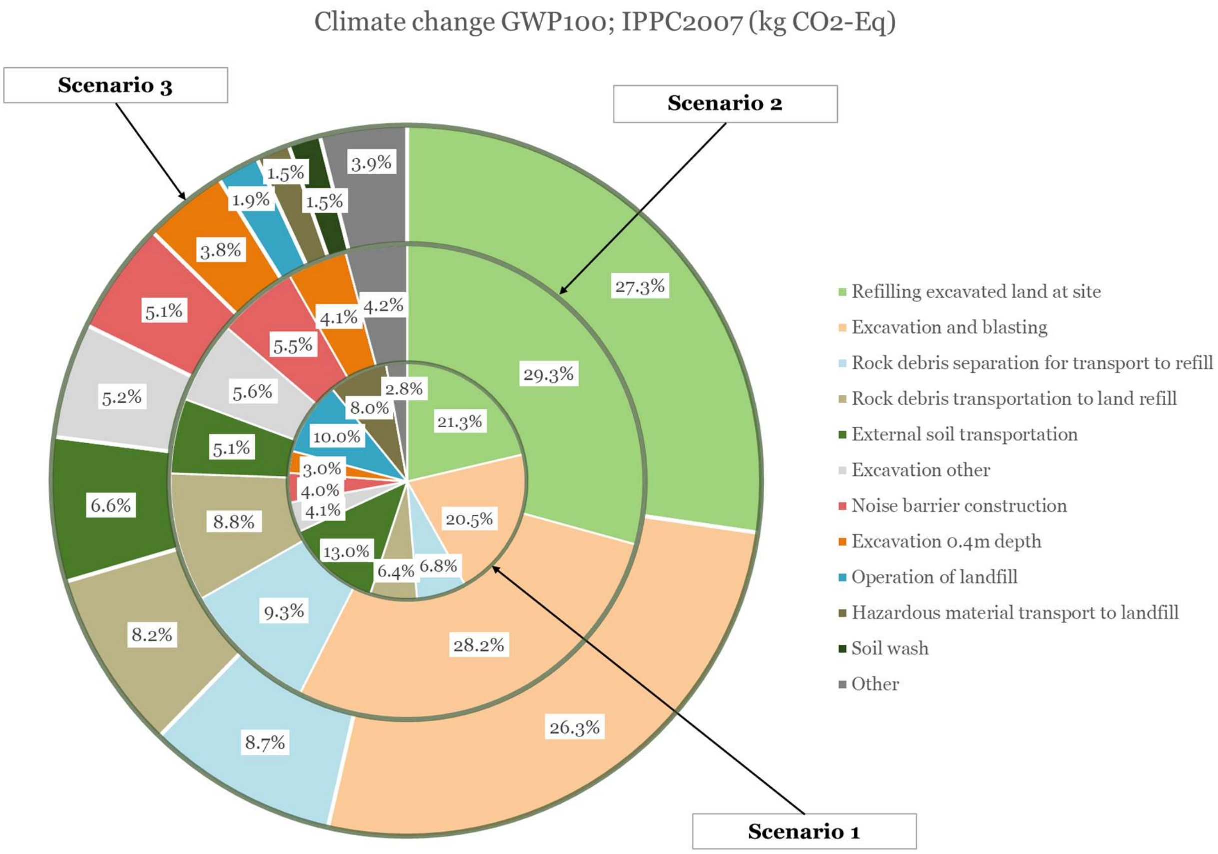

Figure 16: Contribution analysis results of the processes with the highest impact on Climate change GWP100; IPCC2007 (kg CO_2-Eq) for Scenario 1, 2, and 3, in percentages based on the total sum.

There is also a high impact related to landfilling in Scenario 1 with the processes of Operation of landfill (10.0%) and Hazardous material transport to landfill (8.0%) in comparison to Scenario 3 (1.9% and 1.5% respectively), as a higher amount of hazardous waste material needs to be disposed of. Due to the higher amount of fine fraction being classified as hazardous waste that needs to be transported to landfill, the resulting higher amount of external soil that needs to be transported to the site as replacement material for the noise barrier has a higher impact on Scenario 1 (13.0%).

The results of the contribution analysis regarding Ecotoxicity in freshwater (CTUe) are shown in Figure 17, where the highest impacts are related to leaching. For Scenario 1, the leachate and emissions to surface water from the leachate treatment after landfilling has the highest overall impact (41,1%), this impact gets lower for Scenario 3 (5.5%) since a lower amount of hazardous waste material gets transported and disposed of at the landfill than in Scenario 1. The high amount of collected leachate (99.9% for the first 80 years, 87% for the last 20 years) also plays a part in the increased impact.

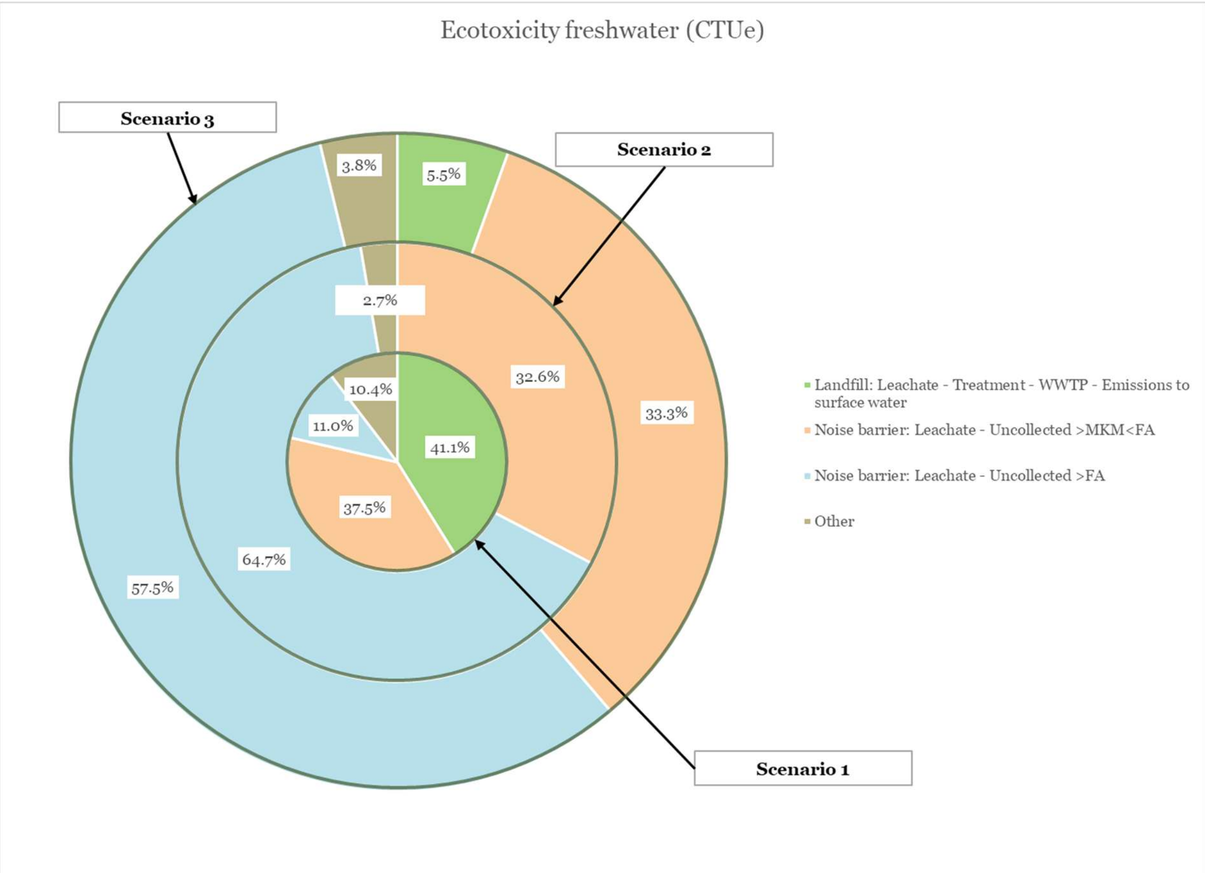

Figure 17: Contribution analysis results of the processes with the highest impact on Ecotoxicity freshwater (CTUe) for Scenario 1, 2, and 3, in percentages based on the total sum.

The impact from the leachate that goes uncollected in the noise barrier are also high, where the uncollected leachate from the material used that are above MKM values, but below FA is high for all three scenarios (37.5% at Scenario 1, 32.6 at Scenario 2, and 33.3% at scenario 3), and the uncollected leachate from material above FA reference values have the highest impact in Scenario 2 (64.7%), with high impact in Scenario 3 (57.5%) and lower impact in Scenario 1 (11.0%). As it is assumed that all leachate generated goes uncollected, and the material mix within the noise barrier, the resulting leachate from the noise barrier leads to a high overall impact on the model.

In summary, the processes with the highest impact related to climate change are Refilling excavated land at site, Excavation and blasting, Rock debris separation for transport to land refill, External soil transportation, Operation of landfill and Hazardous material transport to landfill, while the highest impact related to ecotoxicity in freshwater are Landfill: Leachate - Treatment - Wastewater Treatment Plant (WWTP) - Emissions to surface water, Noise barrier: Leachate - Uncollected > MKM < FA, and Noise barrier: Leachate - Uncollected >FA. All processes and their respective compositions are shown in Table 22.

Table 22: Processes related to the highest impact related to Climate change GWP100; IPCC2007 and Ecotoxicity freshwater with their respective inputs and units.

Composition	Input	Unit
As leachate (>MKM<FA)	1.23E-01	mg/L
Cu leachate (>MKM<FA)	2.41E-02	mg/L
Pb leachate (>MKM<FA)	7.19E-03	mg/L
Zn leachate (>MKM<FA)	6.22E-03	mg/L
As leachate (>FA)	2.41E-01	mg/L
Cu leachate (>FA)	2.79E-01	mg/L
Pb leachate (>FA)	7.73E-02	mg/L
Zn leachate (>FA)	7.62E-01	mg/L
Dumpers, combustion 1L of diesel, 2008/2011	5.33E-05	L/kg Total Wet Weight
RM HS5000M Cummins Stage5	1.52E-05	L/kg Total Wet Weight
Drill, combustion 1L of diesel, 2008/2011	2.63E-05	L/kg Total Wet Weight
Wheel loader, combustion 1L of diesel, 2008/2011	2.16E-05	L/kg Total Wet Weight
Bulldozer, combustion 1L of diesel, 2008/2011	3.38E-05	L/kg Total Wet Weight
Diesel mix, production mix, 2008, EU-27, ELCD	1.71E-02	L/kg Total Wet Weight
Electricity production mix Sweden, high voltage, 2010	1.14E-03	kWh/kg Total Wet Weight
Marginal Electricity Process	4.43E-04	kWh/kg Total Wet Weight
Tovex T	3.70E-04	kg/kg Total Wet Weight
Excavator, skid steer, combustion 1L of diesel, 2008/2011	1.03E-04	kg/kg Total Wet Weight
Process water from surface water, RER, 2005, ELCD	3.19E-08	kg/kg Total Wet Weight
Truck, 28t-32t, Euro6, highway	120.00 (To landfill), 140.00 (External soil to site)	kg*km/kg Total Wet Weight
Rock debris	3.24E+04	kg
External soil	1.4E+03 (S1), 0.4E+03 (S2), 0.55E+03 (S3)	kg
Excavation 0.4 m depth	5.00E+03	kg
Clean soil % after soil wash	85.00	%
Hazardous waste material % after soil wash	15.00	%

4.1.3.2. Sensitivity analysis

The results that show the parameters with the highest impact related to their respective scenario climate change results from the perturbation analysis conducted in EASETECH with a Perturbation Analysis (PA) variation of ±10% are shown in Figure 18 in comparison between Scenario 1 (S1), Scenario 2 (S2) and Scenario 3 (S3). These results are only showing the parameters with SR values above 0.05. More detailed figures for all scenarios are shown in Appendix 4. The parameter with the highest impact related to climate change are Rock debris (total weight of rock debris that gets extracted from excavation and blasting) for all scenarios (0.54 in Scenario 1, 0.73 in Scenario 2, and 0.68 in Scenario 3) due to the high volume and weight of the rock in the model which gets excavated, blasted, separated, transported in-situ, and reused as land refill or for the noise barrier.

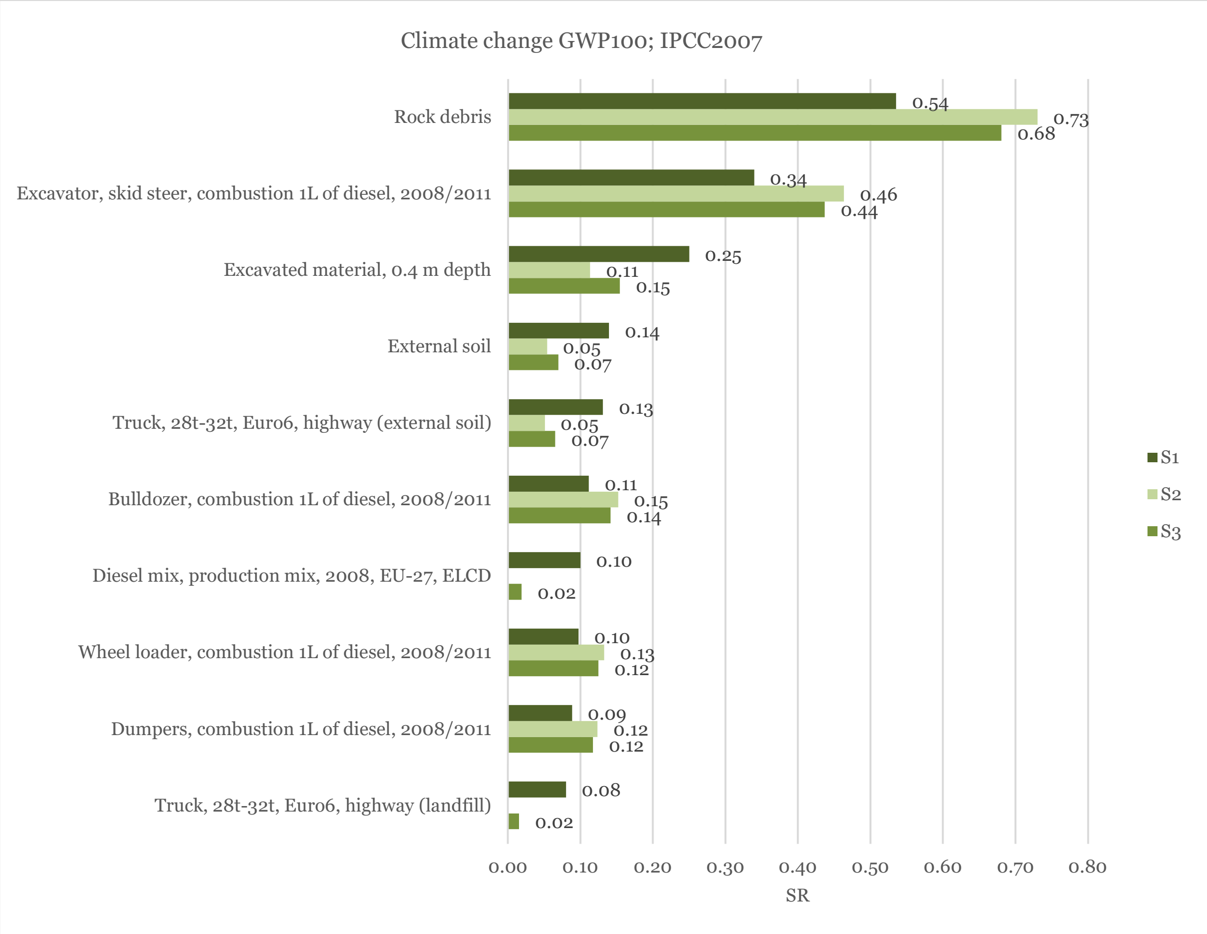

Figure 18: Perturbation analysis results showing the parameters with sensitivity ratio values above 0.05 for Scenario 1 (S1), Scenario 2 (S2), and Scenario 3 (S3), connected to the impact category Climate change GWP100; IPCC2007.

There is also a high SR related to the excavation at 0.4 m depth to extract the fine- and coarse fraction for all scenarios (0.34 in Scenario 1, 0.46 in Scenario 2, and 0.44 in Scenario 3). This is due to the amount of fine- and coarse fraction soil that goes through the processes of excavation, separation, in-situ transportation, land refill, noise barrier fill, in all scenarios, as well as ex-situ transportation and landfilling for Scenario 1 and 3. It also accounts for the fine fraction that gets washed in Scenario 2.

Another material generation parameter that generates higher SR for all scenarios are the external soil (0.14 in Scenario 1, 0.05 in Scenario 2, and 0.07 in Scenario 3) which gets transported to the site and used as filling in the noise barrier. It is also noted that the higher SR between the scenarios reflects the amount that needs to be replaced due to missing fine fraction as filling for the noise barrier.

The machinery used on site also has a higher SR within all scenarios, in particular the excavator (0.34 in Scenario 1, 0.46 in Scenario 2, and 0.44 in Scenario 3), mainly due to a higher fuel consumption than the other machinery used, and to its usage in all excavation points, construction of noise barrier, land refilling, and in the soil washing process.

For the impact category of Ecotoxicity in freshwater, the highest SR for all scenarios (0.47 in Scenario 1, 0.55 in Scenario 2, and 0.54 in Scenario 3) are the excavated material at 0.4 m depth as shown in Figure 19. The parameter related to adjusting the amount of contaminated fine fraction into clean soil and hazardous waste material in the soil washing process has a high impact on the ecotoxicity in freshwater results for Scenario 3, with a SR of 0.48 for the clean soil percentage parameter, and 0.06 for the hazardous waste material percentage parameter. This result is noted as, due to the resulting clean soil and hazardous waste material, the processes of landfilling and noise barrier leachate generation get impacted by this change of ratio.

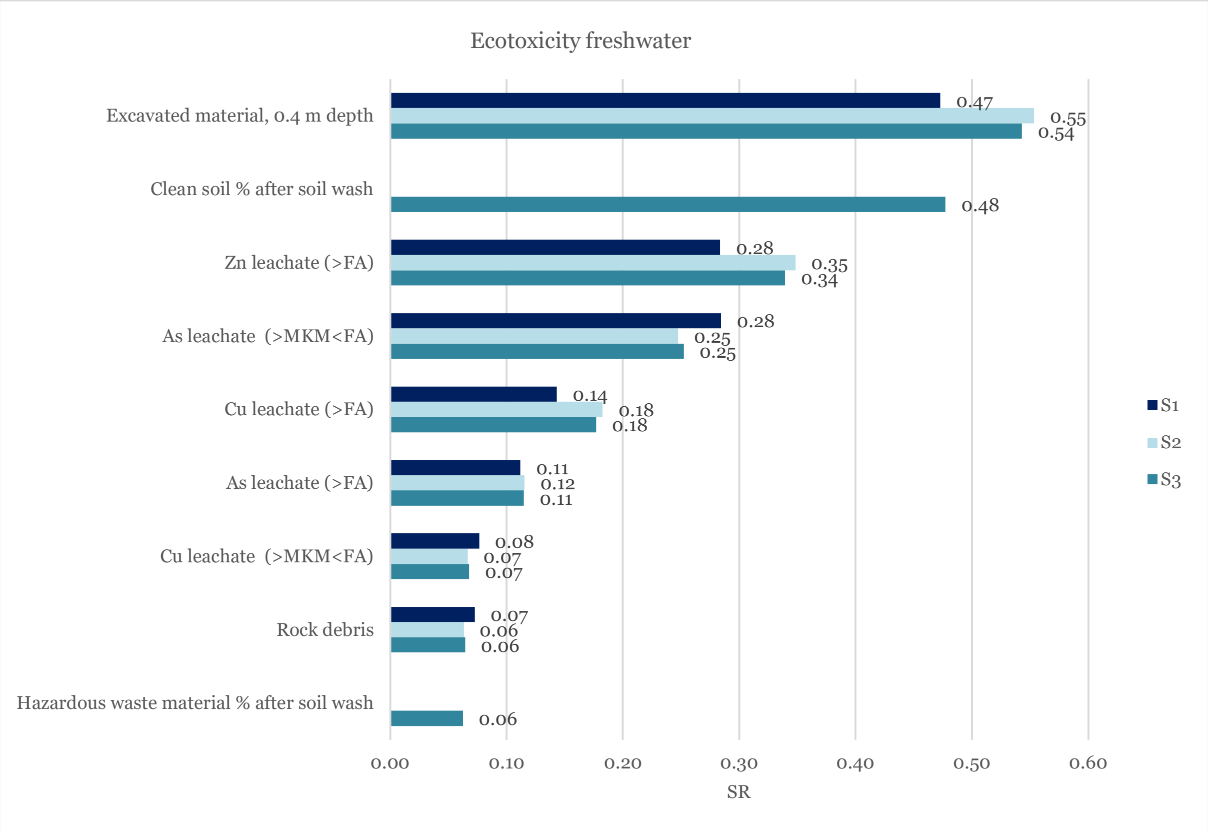

Figure 19: Perturbation analysis results showing the parameters with sensitivity ratio values above 0.05 for Scenario 1 (S1), Scenario 2 (S2), and Scenario 3 (S3), connected to the impact category Climate change GWP100; IPCC2007.

All heavy metals leachate rates, except Pb, show higher SR values, with the leachate of Zn from fractions above FA reference levels showing the highest SR for all Scenarios (0.28 in Scenario 1, 0.35 in Scenario 2, and 0.34 in Scenario 3). The As leachate from fractions with levels above MKM, but below FA, are higher for all scenarios (0.28 in Scenario 1, 0.25 in Scenario 2, and 0.25 in Scenario 3) than their respective SR in fractions with levels above FA. This is most likely because the As leachate stays high for all scenarios within the noise barrier from the coarse fraction, moraine, sewage sludge, and siporex, while the fraction connected to levels above FA, except peat (fine fraction) gets treated at landfill in Scenario 1, and 3, and has an overall lower parameter than the other.

4.1.3.3. Data quality analysis

Table 23 shows the parameters from the perturbation analysis versus their respective data quality from the LCI. These parameters data quality were determined by the calculated DQR results in the pedigree matrix constructed in Microsoft Excel (Microsoft Corporation, 2026), where DQR values above 3 were considered uncertain due to estimates or lacking geographical, technological, temporal relevancy or completeness (European Commission, 2010, p. 332). Values of DQR between 1.6 and 3 were considered basic quality, and values above 3 were considered as poor (European Commission, 2010, p. 332).

Table 23: Parameters DQR results from the LCI compared against their respective SR for Scenario 1, Scenario 2 and Scenario 3.

Parameter	DQR	S1 SR	S2 SR	S3 SR
As leachate (>MKM<FA)	1.7	0.28	0.25	0.25
As leachate (>FA)	1.7	0.11	0.12	0.11
Bulldozer, combustion 1L of diesel, 2008/2011	2.8	0.11	0.15	0.14
Clean soil % after soil wash	2.4	0.00	0.00	0.48
Cu leachate (>MKM<FA)	1.7	0.08	0.07	0.07
Cu leachate (>FA)	1.7	0.14	0.18	0.18
Diesel mix, production mix, 2008, EU-27, ELCD	2.9	0.10	0.00	0.02
Dumpers, combustion 1L of diesel, 2008/2011	3.2	0.09	0.12	0.12
Excavated material, 0.4 m depth (climate change)	2.2	0.25	0.11	0.15
Excavated material, 0.4 m depth (ecotoxicity freshwater)	2.2	0.47	0.55	0.54
Excavator, skid steer, combustion 1L of diesel, 2008/2011	2.8	0.34	0.46	0.44
External soil	3.0	0.14	0.05	0.07
Hazardous waste material % after soil wash	2.4	0.00	0.00	0.06
Rock debris (climate change)	1.7	0.54	0.73	0.68
Rock debris (ecotoxicity freshwater)	1.7	0.07	0.06	0.06
Truck, 28t-32t, Euro6, highway (external soil)	2.8	0.13	0.05	0.07
Truck, 28t-32t, Euro6, highway (landfill)	2.8	0.08	0.00	0.02
Wheel loader, combustion 1L of diesel, 2008/2011	2.9	0.10	0.13	0.12
Zn leachate (>FA)	1.7	0.28	0.35	0.34

The parameters that are the most problematic in the models are the input for Rock debris (climate change), and Excavated material, 0.4 m depth (ecotoxicity freshwater) as shown in Figure 20. This graph shows the correlation between the sensitivity of the parameters (SR) and the uncertainty of the parameters (DQR), where higher SR and DQR results are problematic in the forms of being both highly sensitive and uncertain, which may impact the viability of the model. As leachate (>MKM<FA) and Zn leachate (>FA) are also close to the breaking point shown as a red line where the SR versus DQR result is deemed too high.

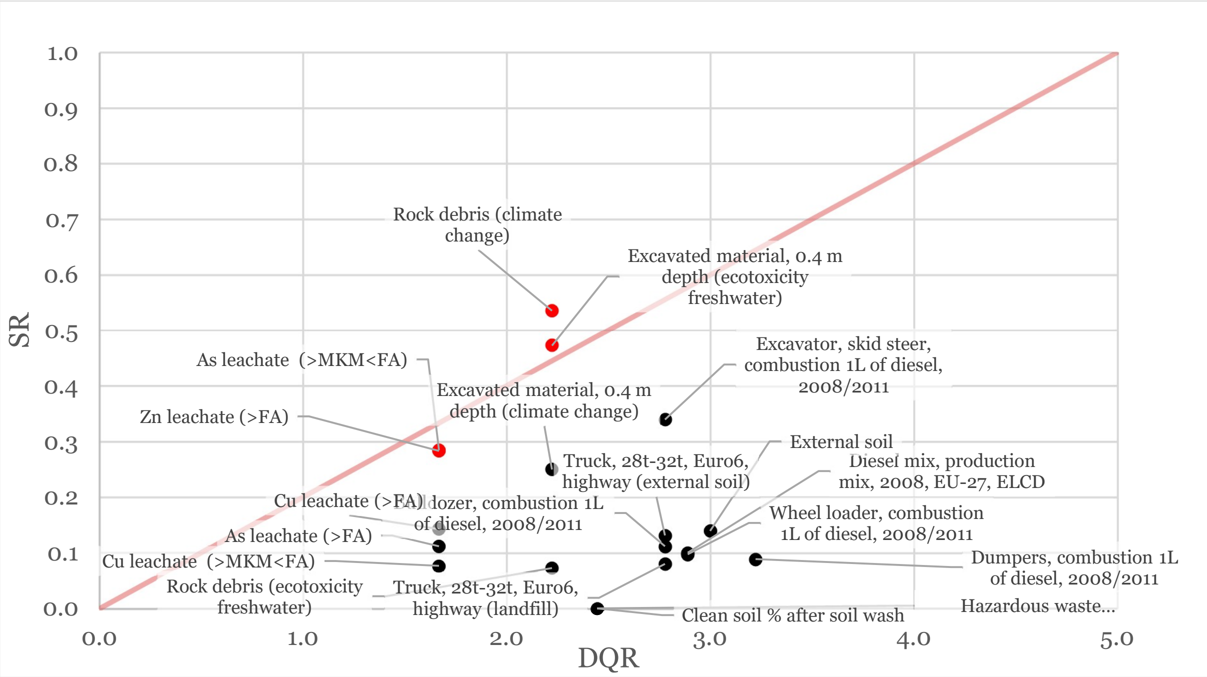

Figure 20: Results of SR versus DQR analysis showcasing the parameters that are high in sensitivity and uncertainty based on their relation to the red line.

These results are related to the processes in the flow related to the material extraction of both rock debris, and the fine- and coarse fraction soil. The FU are also extracted at the 0.4 m depth, and as the leachate properties of this fine fraction is changing between the scenarios (landfilled and treated in Scenario 1, encapsulated in the noise barrier without leachate treatment in Scenario 2, and partly encapsulated in the noise barrier without leachate treatment and partly landfilled and treated in Scenario 3), hence why the parameter are more sensitive for the impact category Ecotoxicity freshwater than Climate change. As fine fraction and peat are the only parameters with As, Cu, Pb and Zn levels above FA, the sensitivity of the rock debris are mainly related to the climate change impact, and not the ecotoxicity in freshwater impact.

These parameters can be problematic to the Monte Carlo simulations moving forward and are worth investigating more to define a higher standard on the parameter value and its correlating uncertainty as standard deviation.

4.1.3.4. Uncertainty propagation

The results for the three scenarios 10000 Monte Carlo simulations on climate change impact are shown in Table 24, where in Scenario 1, the mean is 79.47 kg CO_2-Eq, with a standard deviation of 11.74 kg CO_2-Eq and variance of 137.9 kg CO_2-Eq^2. For Scenario 2, the mean is 62.6 kg CO_2-Eq, with a standard deviation of 10.72 kg CO_2-Eq and variance of 114.8 kg CO_2-Eq^2. Lastly, in Scenario 3 the mean is 58.13 kg CO_2-Eq, with a deviation of 10.55 kg CO_2-Eq and variance of 113.3 kg CO_2-Eq^2.

Table 24: Results from 10000 Monte Carlo simulations for Scenario 1, Scenario 2, and Scenario 3, showing the mean value, standard deviation, variation and variance for the Climate change impact category.

Climate change

Scenario	Mean (kg CO_2-Eq)	St.Dev (kg CO_2-Eq)	Variation (%)	Variance (kg CO_2-Eq)^2
Scenario 1	79.47	11.74	14.77%	137.90
Scenario 2	62.60	10.72	17.12%	114.80
Scenario 3	58.13	10.55	18.15%	111.30

The Monte Carlo results are shown graphically in Figure 21 as relative frequency versus climate change impact in kg CO_2-Eq for all three Scenarios as histograms, where we still have some spikes for all scenarios meaning that there are still some random variables after 10000 simulations. The highest variance occurs in Scenario 1, resulting in a higher spread from the mean than Scenario 2 and Scenario 3. The relative frequency is higher for both Scenario 2 and Scenario 3 than Scenario 1 as well, indicating a higher probability of lower climate change impact. The variation, consisting of the ratio between the mean and the standard deviation, are higher in Scenario 3 than Scenario 1 and Scenario 2, indicating a higher uncertainty which might be caused by the assumed uncertainty for the parameters included in the Monte Carlo analysis (20%).

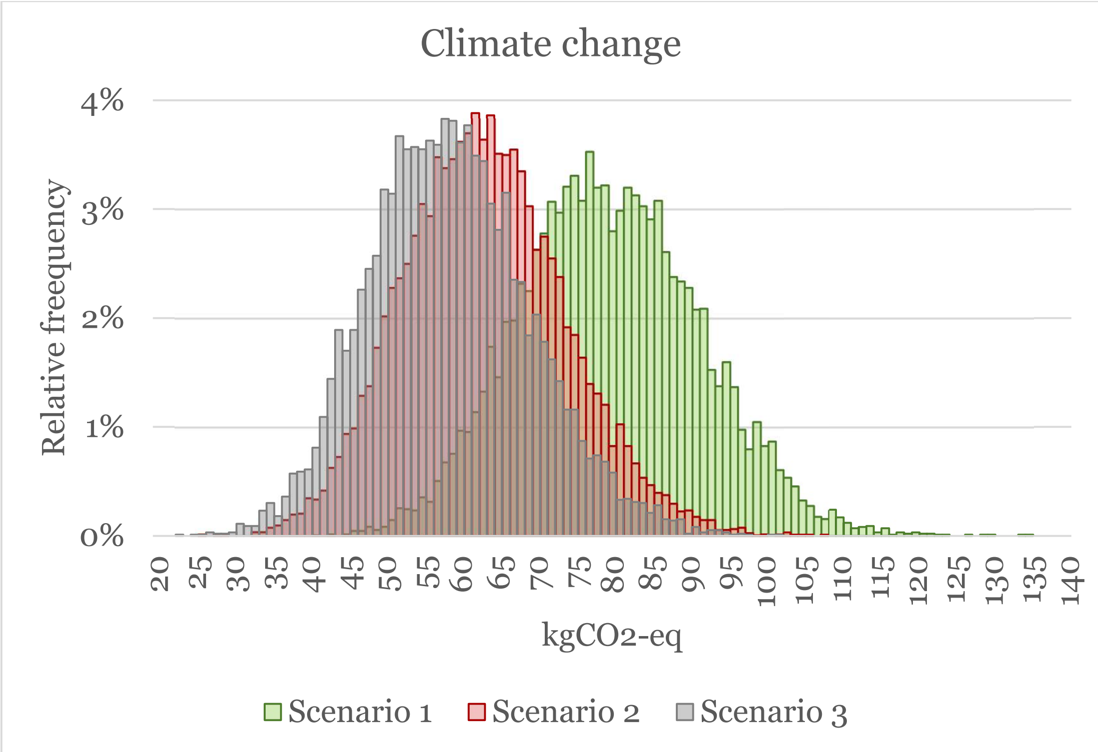

Figure 21: Histograms of 10000 Monte Carlo simulation results for Scenario 1, Scenario 2 and Scenario 3 for the impact category Climate change, in Relative frequency (%) versus climate change impact (kg CO_2-Eq)

The 10000 Monte Carlo simulations on the Ecotoxicity freshwater impact category shows a significantly higher variation uncertainty for all scenarios, especially Scenario 3 (43.33%) as shown in Table 25. The high uncertainty is mainly due to the uncertainty of the leachate parameters which is a result of fluctuations in the lab measurement data which were calculated into a mean average.

Table 25: Results from 10000 Monte Carlo simulations for Scenario 1, Scenario 2, and Scenario 3, showing the mean value, standard deviation, variation and variance for the Ecotoxicity impact category.

Ecotoxicity freshwater

Scenario	Mean (CTUe)	St.Dev (CTUe)	Variation (%)	Var $(CTUe)^2$
Scenario 1	222.30	81.40	36.61%	6625.00
Scenario 2	255.90	109.40	42.75%	11970.00
Scenario 3	248.30	107.60	43.33%	11580.00

The histograms shown in Figure 22 show the near identical shape between the Scenario 2 and Scenario 3 results, as the mean value of ecotoxicity in freshwater impact is 255.90 CTUe in Scenario 2 with a variance of 11970 $CTUe^2$, while the mean value in Scenario 3 is at 248.30 with a variance of 11580 $CTUe^2$. The higher spread depending on the variance in Scenario 2 and Scenario 3 versus Scenario 1 are mainly linked to the uncertainty of the hazardous waste material, which gets landfilled in Scenario 1 where the leachate gets treated, as for Scenario 2 and Scenario 3, a large part of the leachate comes from the noise barrier where it goes uncollected.

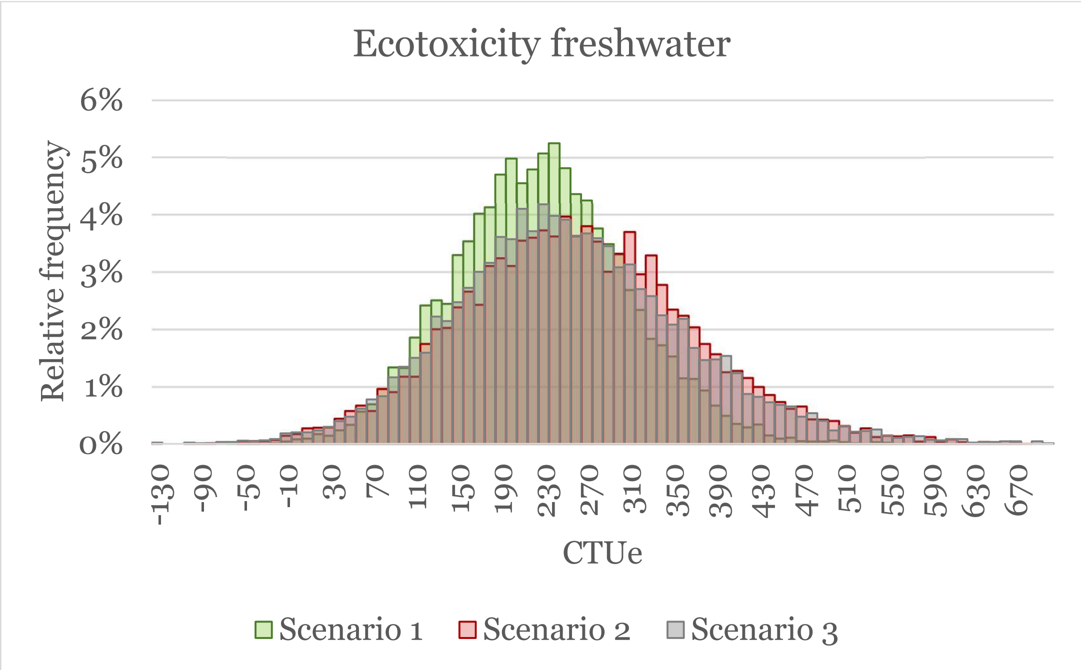

Figure 22: Histograms of 10000 Monte Carlo simulation results for Scenario 1, Scenario 2 and Scenario 3 for the impact category Ecotoxicity freshwater, in Relative frequency (%) versus ecotoxicity in freshwater impact (CTUe).

Note that there are potential negative results in the Monte Carlo simulations, which is incorrect in theory, but might have been caused by the possible outcome of negative values using normal distribution (Devore, 2012, pp. 152–153), which were used due to its compatibility with the Monte Carlo simulation function in EASETECH. They might also be the outcome of miscalculations within the software. These negative values only accounted for a small part of the total 10000 simulations (under 0.2%) and were determined to not affect the overall mean results but were included to showcase the uncertainty of the models.

4.1.3.5. Discernibility analysis

Table 26 shows the difference between the three scenarios for their respective Monte Carlo mean value results related to the impact categories Climate change and Ecotoxicity freshwater. The mean value of climate change impact for Scenario 1 is 21.4 kg CO_2-Eq higher than Scenario 2, and 16.87 kg CO_2-Eq higher than Scenario 3, where the mean value of Scenario 3 is 4.47 kg CO_2-Eq higher than Scenario 2. The mean value of Scenario 2 is lower than both Scenario 1 and Scenario 3. The mean value of ecotoxicity in freshwater impact in Scenario 2 is 33.60 CTUe higher than Scenario 1, and 7.60 CTUe higher than Scenario 3. The mean value of Scenario 3 is 26.00 CTUe higher than Scenario 1.

Table 26: Difference between the mean results of 10000 Monte Carlo simulations connected to the Climate change and Ecotoxicity freshwater impact categories for all three scenarios.

Climate change (kg CO_2-Eq)

	Scenario 1	Scenario 2	Scenario 3
Scenario 1	-	-21.34	-16.87
Scenario 2	21.34	-	4.47
Scenario 3	16.87	-4.47	-

Ecotoxicity freshwater (CTUe)

	Scenario 1	Scenario 2	Scenario 3
Scenario 1	-	33.60	26.00
Scenario 2	-33.60	-	-7.60
Scenario 3	-26.00	7.60	-

Table 27 shows the discernability analysis results for all the 10 chosen impact categories related to environmental impacts in the forms of natural environment, and/or natural resources impacts (Climate change, Ecotoxicity freshwater, Ozone depletion, Terrestrial acidification - Accumulated, Eutrophication terrestrial - Accumulated, Eutrophication freshwater, and Eutrophication marine). This table is a heatmap where percentages above 50% are shown as red, and percentages below 50% are shown as green. Results close to 50% are shown as yellow, as the results between the scenarios are close to- or not considered discernible. These results are based on 10000 Monte Carlo simulations for each scenarios impact category and showcases the percentages where, for example, the results of Scenario 1 are higher than Scenario 2, and Scenario 3 and vice versa.

For example, the Climate change impact category Monte Carlo simulations are about 90.54% of the cases for 10000 simulations (approximately 9054 of 10000 simulations), higher than Scenario 2, and 85.37% of the cases higher than Scenario 3. Scenario 3 is also in 60.35% of the cases higher than Scenario 2. Scenario 2 has overall a lower result than Scenario 1 and 2.

The Ecotoxicity freshwater impact category Monte Carlo simulations shows that Scenario 2 is in 59.80% of the cases higher than Scenario 1, and in 51.70% of the cases higher than Scenario 3. Scenario 3 is however, in 56.72% of the cases higher than Scenario 1. We also see that the results of the Ecotoxicity freshwater Monte Carlo simulations are close to 50% across all scenarios, making the difference less discernible.

Table 27: Discernability analysis results for impact categories related to environmental impacts (natural environment and/or natural resources)

Natural environment / Natural resources

		Scenario 1	Scenario 2	Scenario 3
Climate change	**Scenario 1**	-	9.46%	14.63%
	Scenario 2	90.54%	-	60.35%
	Scenario 3	85.37%	39.65%	-
Ecotoxicity freshwater	**Scenario 1**	-	59.80%	56.72%
	Scenario 2	40.20%	-	48.30%
	Scenario 3	43.28%	51.70%	-
Ozone depletion	**Scenario 1**	-	7.09%	99.67%
	Scenario 2	92.91%	-	100.00%
	Scenario 3	0.33%	0.00%	-
Terrestrial acidification, Accumulated	**Scenario 1**	-	14.74%	20.14%
	Scenario 2	85.26%	-	58.63%
	Scenario 3	79.86%	41.37%	-
Eutrophication Terrestrial, Accumulated	**Scenario 1**	-	30.01%	34.09%
	Scenario 2	69.99%	-	54.86%
	Scenario 3	65.91%	45.14%	-
Eutrophication Freshwater	**Scenario 1**	-	0.04%	0.99%
	Scenario 2	99.96%	-	91.46%
	Scenario 3	99.01%	8.54%	-
Eutrophication Marine	**Scenario 1**	-	32.10%	36.13%
	Scenario 2	67.90%	-	54.01%
	Scenario 3	63.87%	45.99%	-
Total	**Above 50%**	**11**	**2**	**8**

Scenario 1 is in 11 of the cases higher than both Scenario 2 and Scenario 3 for all impact categories related to environmental impact, while Scenario 2 is only higher than Scenario 1 and Scenario 3 in 2 of the cases. Scenario 3 is in 8 of the cases higher than Scenario 1 and Scenario 2.

Table 28 shows the discernability analysis results for all the 10 chosen impact categories related to human health impacts (Climate change, Ozone depletion, Human toxicity - Cancer effects, Human toxicity - Non-cancer effects, and Particulate matter) for all three scenarios. For ozone depletion impact we can see that Scenario 3 are in 99.67% of the cases higher than Scenario 1, and 100% of the cases higher than Scenario 2. This is due to the high impact on ozone depletion from the electricity required to wash the large amount of hazardous fine fraction soil. The 10000 Monte Carlo simulations of Human toxicity - Cancer effects, are close to 50% between all three scenarios and are less discernible, however, the impact of Scenario 1 is in 64.54% of the cases higher than Scenario 2, and 63.09% of the cases higher than Scenario 3 for non-cancer effects. Although the uncollected leachate from the noise barrier plays the largest role across all scenarios, the impacts of operating the landfill and the WWTP leachate treatment increases the negative impacts of Scenario 1.

The results for negative health impacts from particulate matter are in 95.26% of the cases higher in Scenario 1 than Scenario 2, and in 82.89% of the cases higher than Scenario 3. Scenario 3 are also in 77.72% of the cases higher than Scenario 2. The major processes related to the impact are the processes related to excavation and blasting of rock mountains for all three scenarios, however, the negative impact from landfilling and soil washing exceeds the results for Scenario 1 and Scenario 3, contra Scenario 2

Table 28: Discernability analysis results for impact categories related to human health impacts.

Human health			Scenario 1	Scenario 2	Scenario 3
	Climate change	**Scenario 1**	-	9.46%	14.63%
		Scenario 2	90.54%	-	60.35%
		Scenario 3	85.37%	39.65%	-
	Ozone depletion	**Scenario 1**	-	7.09%	99.67%
		Scenario 2	92.91%	-	100.00%
		Scenario 3	0.33%	0.00%	-
	Human toxicity, cancer effects	**Scenario 1**	-	45.97%	46.09%
		Scenario 2	54.03%	-	50.39%
		Scenario 3	53.91%	49.61%	-
	Human toxicity, non-cancer effects	**Scenario 1**	-	35.46%	36.91%
		Scenario 2	64.54%	-	51.44%
		Scenario 3	63.09%	48.56%	-
	Particulate matter	**Scenario 1**	-	4.73%	17.10%
		Scenario 2	95.26%	-	77.72%
		Scenario 3	82.89%	22.27%	-
	Total	**Above 50%**	**9**	**0**	**6**

In total, Scenario 1 is higher than Scenario 2 and Scenario 3 in 9 of the cases, while Scenario 2 is never higher than Scenario 1 or Scenario 3 in any case. Scenario 3 is higher than Scenario 1 and Scenario 2 in 6 of the cases. This means that in none of the cases for all impact categories related to human health impacts are Scenario 2 higher than the other two scenarios.

In summary, after 10000 Monte Carlo simulations conducted in EASETECH across all 10 chosen impact categories related to environmental- and human health impacts with the parameters determined in Chapter 3.2.4.4 Uncertainty propagation: Monte Carlo, Scenario 1 cause, in 20 of the total cases higher environmental- and human health impact than both Scenario 2 and Scenario 3. Scenario 2 cause only in 2 of the total cases higher environmental- and human health impact than Scenario 1 and Scenario 3. These two cases are related to the increased freshwater ecotoxicity impact of caused by the uncollected leachate from the noise barrier.

Scenario 3 cause in 14 of the total cases, higher environmental- and human health impact than Scenario 2 and Scenario 1. Scenario 3 will almost always cause a higher ozone depletion impact than the other two scenarios, which is caused by the high amount of electricity needed to clean the high amount of fine fraction.

4.2 Economic analysis

This section covers the results of the economic analysis to showcase the difference between the economic impacts between the three scenarios to handle and remediate the FU.

4.2.1 Economic results

The economic evaluation results are shown in Table 29 and Figure 23, in SEK per handled FU (1 tonnes of hazardous fine fraction) based on the difference between the scenarios. The hazardous material transport cost is higher for Scenario 1 as a higher amount of hazardous waste material needs to be transported from point A to point B in Scenario 1, than Scenario 2 and Scenario 3. This additionally results in a higher amount of external soil that needs to be purchased as a replacement to fill the material criteria for the noise barrier construction, thus increasing the cost of external soil in both Scenario 1, and Scenario 3. The higher amount of hazardous waste material that needs to be landfilled also increases the cost of depositing the hazardous waste, and landfill tax. The costs of depositing the hazardous waste material and the landfill tax that needs to be covered are fully bypassed in Scenario 2 as all hazardous waste material gets encapsulated inside the noise barrier in-situ. The cost of soil washing and transporting the washed soil only occurs in Scenario 3.

Table 29: Costs associated with landfilling (Scenario 1), encapsulating in noise barrier (Scenario 2), and soil washing and landfilling (Scenario 3) the 1 tonne hazardous fine.

Cost	Scenario 1	Scenario 2	Scenario 3
Hazardous material transport (SEK/tonne)	251.71	4.08	37.76
External soil (SEK/tonne)	765.63	218.75	300.78
Depositing hazardous waste (SEK/tonne)	670	0	100.5
Landfiill tax (SEK/tonne)	750	0	112.5
Washed soil transported to noise barrier (SEK/tonne)	0	0	3.47
Soil wash (SEK/tonne)	0	0	614.64
Total cost (SEK/tonne)	**2437.34**	**222.83**	**1169.65**

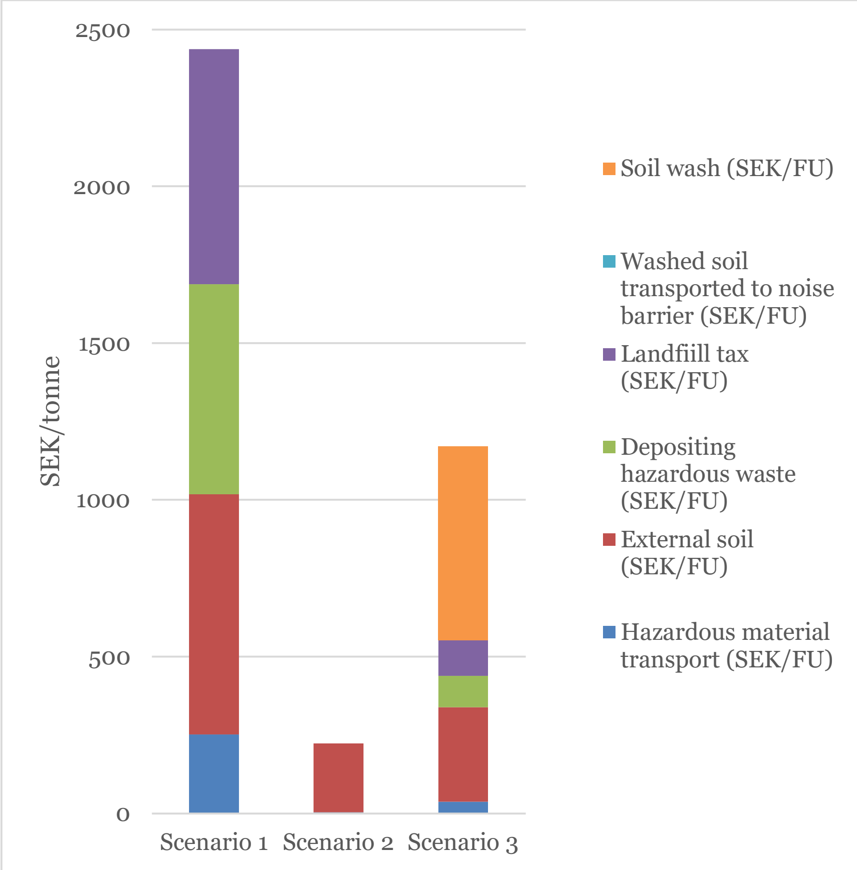

Figure 23: Graph showcasing the costs associated with landfilling (Scenario 1), encapsulating in noise barrier (Scenario 2), and soil washing and landfilling (Scenario 3) the 1 tonne hazardous fine fraction to immobilize contaminants under critical levels.

In total, handling the 1 tonne hazardous fine fraction in order to immobilize the heavy metal contaminants between the scenarios, the least expensive alternative is Scenario 2 at 222.83 SEK/tonne, compared to Scenario 1, being the most expensive alternative at 2437.34 SEK/tonne, and Scenario 3 at 1169.65 SEK/tonne.

5 DISCUSSION

This section covers the discussion of methods used, end results and its limitations.

5.1 Literature review

Most of the information gathered about common soil remediation techniques were gathered from The Swedish Geotechnical Society website, Åtgärdsportalen. This website is financed by the Swedish EPA, Sveriges Geotekniska Institut (SGI) and Trafikverket, and may be a source of information about different methods used in Sweden (Svenska Geotekniska Föreningen, 2026a). However, as this information was used to determine the potential alternatives for soil remediation at Näsudden, in combination with data scarcity and a reliance on secondary data and estimates from outside the country, the actual potential alternatives might not be fully correct. What may have worked in other countries might not work in northern Sweden, considering the complexity of the soil structure and the cold northern climate. Heavily relying on information connected to Swedish cases may also lower the quality of the report on a global scale. Due to the limited time availability of the project, new and modern techniques have thus been excluded, except for biochar remediation. There could therefore be other alternative methods that may be suitable for the project, which have not been investigated in this study.

There was also a high reliance on using site-specific documents and information provided by the municipality, and as these reports were made by third-party companies, the amount of biased information and results are uncertain. However, as the availability of information regarding the project are limited, the documents provided were used where it was deemed necessary.

5.2 Interpretation

This section includes discussion of the results gathered from the LCA as included in the interpretation to align with ISO 14040 and 14044 combined with the economic analysis.

5.2.1 Consistency check

Primary data only consisted of measurements regarding the soil volume and the contaminants. Thus, secondary data had to be gathered for all processes and parameters outside this scope. This means that some data regarding inputs and outputs were estimates and calculated based on similar case studies and databases. Some equations, in particular regarding machinery as shown in Appendix 2, were assumed based on the data collected and might not have been calculated correctly. In a real-life scenario, these results would most likely vary to an extent. However, due to the availability and the time availability of the study, a broader approach had to be made. This means that the end results from all scenarios will most likely differ from the reality, in all aspects of environmental, health and economic impact. Information and data directly from manufacturers, operators and service providers connected to the relevant processes and parameters would strengthen the results even further.

The uncertainty for all parameters except the ones related to As, Cu, Pb and Zn were assumed to be 20%, which could have skewed the end results of the Monte Carlo simulations. Stronger uncertainty numbers could have been gathered from similar case studies with more exact deviations to its relative data variable. For example, uncertainty for specific machineries could have been gathered from studies related to specifically using these types of machinery for excavation.

The economic analysis of the study is also on a limited basis and only shows the economical differences between the scenarios connected to the handling and remediation of the FU, which excluded any environmental costs. In reality, Scenario 2 might for example have a higher overall cost due to an increased need for handling and monitoring the uncollected leachate from the noise barrier. If the economic analysis would have followed the basics of a fully-fledged LCC study, stronger parameters regarding the costs and investments related to all processes within the life cycle for each scenario could have been gathered. The potential difference in these results could potentially open to a different viewpoint for the municipality to choose an alternative for handling the fine fraction soil.

5.2.2 Environmental, human health and economic impact results

The end results related to environmental, human health and economic impact are overall the highest for the base scenario of excavation and landfilling modelled in Scenario 1 making it the least sustainable and beneficial alternative. The 10000 Monte Carlo simulations done for the 10 chosen impact categories shows that Scenario 1 is in total 20 of the cases higher than both Scenario 2 and Scenario 3 and will thus most likely lead to an elevated environmental and health impact if fully implemented. The cost difference between this scenario and the other two are also significant, as the cost to handle and remediate the hazardous fine fraction to immobilize contaminants under critical levels is almost double to the second most expensive option, Scenario 2. The high volume of contaminated fine fraction soil that has to be deposited at the Dåva landfill could also be too high to handle, and the higher amounts of transportation needed to transport the hazardous soil ex-situ as well as transporting external soil to the site could potentially lead to increased amounts of traffic accidents, further increasing the negative human health impacts of the solution.

Scenario 3 has the potential to lower the negative impacts of leachate from the hazardous fine fraction by cleaning the soil to reach As, Cu, Pb and Zn levels below the FA reference levels if the efficiency of the system is on par with the removal efficiencies of 70.7%, 79.7%, 80.1% and 71,2% for As, Cu, Pb and Zn respectively. However, as this fraction only makes up about 15% of the total material fractions needed to construct the noise barrier, the discernibility between washing the soil before reusing encapsulation compared to encapsulating it without pre-treatment as done in Scenario 2 are minimal considering freshwater ecotoxicity. The high amounts of chemicals needed to wash 100000 tonnes of soil might also cause a higher impact than what has been modelled, as the washing agents were excluded from the soil washing leading to underestimated end results with higher uncertainty. The logistics needed to wash this amount of soil could also be a hinderance for the solution, as well as the uncertainty of the time availability to wash in a sub-arctic climate, as the washing would only be possible outside of winter months.

The same leachate properties for the noise barrier were used across all scenarios, which could potentially have overestimated the freshwater ecotoxicity impact from uncollected leachate in Scenario 3. The levels of As, Cu, Pb and Zn gets reduced before encapsulation from the soil washing process, but the leachate parameters are as high as Scenario 2, which may have skewed the negative impacts from uncollected leachate. The levels of leachate from this cleaned fine fraction might not be as high as un-treated hazardous fine fraction in a real-life scenario and needs to be investigated further in more depth.

If Skellefteå municipality decides to try a mobile on-site soil washing technique, it is recommended that they conduct a smaller scale pilot study at the site to determine whether the chosen washing chemicals are fitting, if the removal efficiency is as high as expected, and if the fine fraction soil structure are not too fine, or too organic or humid for the project (Hölzle et al., 2025, p. 6; H. Zhang et al., 2022, p. 15).

Scenario 2 is overall the most sustainable and beneficial solution to handle and remediate the fine fraction, if the long-term effects of the noise barrier is excluded. As across the 10000 Monte Carlo simulations, the results across the impact categories are only higher than the other two scenarios in two of the cases, both occurring within the Ecotoxicity freshwater impact category. This is mainly due to the increased leachate of As, Cu, Pb and Zn above critical levels that occurs when the hazardous fine fraction goes untreated combined with uncollected leachate. The uncollected leachate plays a major part in increasing the negative impacts on the environment, as it accounts to approximately 67% of the freshwater ecotoxicity. This solution does however reduce the negative impacts from transportation, as it would remove the need for any ex-situ hazardous soil waste completely, further mitigating the environmental and potential human health impact an approximately 3300 round trip truck transportation could produce.

The solution is however highly uncertain, as the noise barrier is mainly constructed using organic material on a site located in a sub-arctic climate that may experience relatively high yearly precipitation of approximately 493.9 mm/year, which could elevate the leachate and impact the stability of the construction. With a higher leachate that goes uncollected comes higher negative impact to the ecosystem and the human health, which would also lead to higher costs related to handling and measuring the leachate in-situ. For example, monitoring the noise barrier could cost around 15000 SEK/ha (Hansson, 2023, p. 5), and handling and treating the leachate could cost around 20-230 (Naturvårdsverket, 2008, p. 20) depending on for example, methods used, amount of leachate and the leachate properties. The costs could be even higher, as it could affect the soil, groundwater sources and potentially the water of Gulf of Bothnia surrounding the site, and if monitoring and handling the leachate must be done annually, the costs would increase significantly over time. The uncertainty of the stability of the noise barrier might also impact future costs, as the organic construction material might decay over time, thus resulting in costs related to reconstruction and maintenance.

If Scenario 2 is implemented, it is recommended that further effectivization of the noise barrier should be investigated. This effectivization could include installing a leachate collection system or combining the noise barrier with a more long-term remediation technique such as phytoremediation.

There is also a high variance connected to the input parameters of leachate for some of the heavy metals. This is most likely an effect of a high uncertainty percentage as standard deviations for the inputs. For example, As leachate from fractions with levels above FA has an uncertainty of approximately 71.6%, yet it still has a low SR versus DQR result due to its low sensitivity and high primary data quality from being relatively new site-specific measurements. The high uncertainty is however a result of highly fluctuating lab results, with a high variety, which could potentially be expected at the site due to its large volume and heterogeneous soil properties.

The primary data points DQR results were overall lower than the secondary data points (see Appendix 3) due to previous in-situ XRF and lab measurements. The same results were gathered by Ai et al. (2026, pp. 5–6) in their study "Investigating the impacts of data sourcing in LCA using uncertainty-sensitivity analysis with a case study of soil remediation" where they investigated the difference and substitutability of primary data versus secondary data using soil washing processes similar to the modelled system in Scenario 3. The study also concluded that the negative impacts related to human health were higher than the environmental impacts for soil washing, which is a different result from the scenario modelled for Näsudden, where the environmental impacts are higher due to ecotoxicity. They do however acknowledge a high impact from the usage of lime, which were not included in the soil washing process modelled for Scenario 3 at Näsudden (Ai et al., 2026, pp. 5–6).

The results from Scenario 1, Scenario 2 and Scenario 3 shows the highest impact across all scenarios for most environmental impact categories from processes related to the excavation, blasting, machinery usage, and refilling connected to the rock mountains and rock debris at the area. In their study "Biofuel or excavation? - Life cycle assessment (LCA) of soil remediation options", Suer & Andersson-Sköld (2011, pp. 975–976) experienced high results in their modelled excavation and refill scenario related to their chosen environmental impact categories, which were primarily caused by the landfill and the soil transportation to the landfill. The same is concluded by Lemming et al. (2010, p. 122) which states the ex-situ transportation as a high contributor to environmental impacts. Our results, however, shows that the landfill process and soil transportation accounts for approximately 10% respectively 8% of the total impact on climate change. If we would disregard the climate impact from excavation and blasting of rock mountains and its sub-processes, landfilling and soil transportation (both external soil to the site, and transporting the hazardous fine fraction to the landfill) would indeed most likely have the highest environmental impact.

Another impact worth noting is the processes where heavy machinery is used. There is a high environmental impact from the diesel consumption from the dumpers, separators, drills, wheel loaders, bulldozers, and excavators used at the site as these machines must dig, drill, carry, separate, and transport large amounts of earth material. The same findings were made by Lemming et al. (2010, p. 122) in their review of LCA studies connected to soil and groundwater remediation, that the consumption of diesel and electricity in-situ played a major role in environmental impacts. There is however a high uncertainty related to the chosen machinery parameters, as most of the fuel consumption parameters gathered and calculated have a decently high DQR indicating a lower quality (see Appendix 3).

5.2.3 Limitations in results

Due to the limited time availability to conduct the project, several remediation techniques were not included in the literature review. This might have resulted in potential remediation techniques that could have been plausible to model as a scenario. The complex nature of the area in regards of heterogeneity of contaminants, soil structure, time availability and the volumes of remediation that is needed, made it difficult to connect the literature review research with the sites criterias. A more thorough literature review could potentially open to other remediation techniques that has not been used for modelling and having more than three scenarios would lead to more results for comparison. However, after discussions with Skellefteå municipality, their interest in investigating soil washing as a potential solution to the Näsudden project, both due to them having discussed it inhouse in the past, as well as the availability of mobile on-site soil washing near the Näsudden site, solidified it as a valuable solution for further investigation.

The transportation of hazardous waste material only considers the transported waste in kg*km, which results in the total weight of hazardous waste material multiplied by a one-way trip to from Näsudden to the Dåva landfill in Umeå. This means that return trips have been excluded for all external transportation. It is however expected that around 3300 individual truck transportations are needed in Scenario 1 due to the large-scale of the hazardous fine fraction that needs to be landfilled. Thus, the environmental impact from this transportation could be higher than the results may show due to individual engine start- and stops. The same logic is applied to the external soil being transported to the site. Nor has the transportation of equipment or construction of the mobile soil washing unit been considered. Adding these parameters into the models of Scenario 1, Scenario 2, and Scenario 3 could increase the negative environmental and human health impacts even further, which could potentially benefit the Scenario 2 results, as it is not dependant on these processes except transportation of external soil to the site.

For Scenario 1, it is assumed that, based on XRF and lab measurements, the top layer of 0-0.1 m consists of soil that contains hazardous levels of As, Cu, Pb and Zn above the FA reference levels. As, Pb, Cu, Hg and Zn levels above the MKM reference levels can however be found beneath this layer, downwards to approximately 0.4m (Tyréns AB & Skellefteå Kommun, 2017, pp. 22-27 Bilaga 4). If, after excavation, these levels get mixed due to the excavation or don't comply with the regulations affecting the construction of the industrial complex, it is assumed that all soil excavated on a depth of 0.4 m needs to be remediated. This means that all of the 500000 tonnes excavated soil needs to be transported and landfilled (J. Wellenius & O. Rydlinge, personal communication, March 2, 2026). This potential outcome has not been included in the study. The XRF and lab results of contaminants within the area are spread out across the site, and not just from the site of 0.4 m depth excavation. This makes the contaminant levels uncertain on the other excavation sites. This also means that the assumed %TS of heavy metals and leachate properties might not be accurate, as parts of the soil structure from these sites might experience elevated or decreased levels of contamination. Thus, the real-life scenario negative impacts of leaching that occurs from the landfilling and noise barrier might not be fully correct.

Crushing of large rocks from excavation and blasting of rock mountains, and excavation of coarse fraction has not been included due to limited data availability. If this process would be needed, it could potentially increase the impacts of the processes related to the rock debris significantly depending on the volume of large-scale rocks that will result from all excavation processes.

No cost data were used for any environmental impacts. As the leaching is higher in Scenario 2, the costs of handling and monitoring the leachate in-situ could potentially be higher. This extra cost has however not been included in the economic analysis.

The impacts related to the production and usage of washing agents in the soil washing process in Scenario 3 have not been included, as the washing agents were excluded entirely from modelling due to the non-compatibility between gathered ecoinvent data and the EASETECH software. By excluding these parameters, the environmental, human health and economic impacts may have been underestimated for the scenario, as the calculated amount of washing agents needed to clean 100000 tonnes of hazardous fine fraction is relatively high. It is thus advised to include these parameters in future LCA research when modelling a soil washing system.

Scenario 3 is almost always (approximately 100% of the 10000 Monte Carlo simulations) causing higher ozone depletion impact than Scenario 1 and Scenario 2, with an average impact of 6.44E-08 kg CFC-11 Eq compared to 3.27E-08 CFC-11 Eq in Scenario 1 and 2.20E-08 kg CFC-11 Eq in Scenario 2. It is possible, but unlikely that the electricity usage of the soil washing system cause such a high impact in relation to the other processes within the system. This parameter has a DQR of 3.9 as shown in Appendix 3, which indicates it is of poor quality and is thus sensitive to high uncertainties. Further investigation should be made using either a scenario analysis, with a lower electricity usage, or with stronger data from primary electricity sources and from mobile soil washing service providers in the area.

5.3 Connection to the Sustainable Development Goals (SDG)

This study mainly aligns with the Sustainable Development Goals; *SDG 3. Good health and well-being, SDG 12. Responsible Consumption and Production,* with the targets:

Target 3.6 Road traffic accidents (United Nations, 2025, p. 45)*:*
The amount of road traffic accidents related to heavy truck transportation that may result

from the high amount of needed fine fraction transportation to landfill in Scenario 1 could be mitigated if Scenario 2 or Scenario 3 is implemented instead.

Target 3.9 Health impact of pollution (United Nations, 2025, p. 45)*:*
By remediating the hazardous soil at Näsudden, illnesses from future heavy metal exposure can be mitigated at the site. Encapsulating the hazardous fine fraction inside the noise barrier in Scenario 2 may limit the negative human health impacts as it could potentially immobilize the heavy metals and prevent further exposure, however, the risks of leachate from the encapsulated hazardous fine fraction remains and should be mitigated further.

Target 12.2 Sustainable use of natural resources (United Nations, 2025, p. 45)*:*
Constructing the noise barrier at Näsudden with reused extracted material, combined with encapsulating the fine fraction inside the noise barrier in Scenario 2, or soil washing the fine fraction before encapsulation in Scenario 3, will lead to a decreased need for external material needed for the noise barrier.

Target 12.4 Managing chemicals and wastes (United Nations, 2025, p. 45)*:*
Scenario 2 and Scenario 3 would lead to reduced environmental impact in comparison to Scenario 1. It could also promote a safer handling of large amounts of soil waste, as they would exclude waste transportation fully in Scenario 2, or limit it in Scenario 3. Lowering the levels of heavy metals in Scenario 3 before reusing it in the noise barrier could reduce the hazardousness and leaching of the fine fraction in comparison to Scenario 2. Transporting the hazardous fine fraction off the site for landfilling in Scenario 1 would however place the contaminated soil in closed conditions, where the risks of leachate can be monitored.

Target 12.5 Reduction in waste generation (United Nations, 2025, p. 45)*:*
Scenario 2 and Scenario 3 would greatly reduce the volume of hazardous waste that needs to be disposed of. This would lower the strain the large amounts of soil waste would have on the landfill at Dåva, Umeå as investigated in Scenario 1.

6 CONCLUSIONS

The aim of this study was to investigate alternative solutions to handling and remediate a volume of hazardous heavy metal contaminated soil at Näsudden, located outside the town of Skellefteå in Northern Sweden. The topsoil at the site, particularly the fine fraction, has had increased levels of As, Cu, Pb and Zn above the national hazardous waste reference limits, as a result from historical aerial pollution from an industrial complex nearby. To remediate the soil to a safe limit to construct an industrial compound at the site, Skellefteå municipality needs a sustainable solution that is mitigating the environmental, human health and economic impacts a large-scale excavation and remediation project can have. A common solution to these types of projects in Sweden are through excavation and landfilling, which for the case at Näsudden would require a significant amount of excavated hazardous soil waste transportation via truck to the Dåva landfill in the nearby city of Umeå.

The study included a literature review where different remediation techniques commonly used in Sweden were investigated and compared against the soils properties and its heavy metal content, the capacity that needs to be remediated, the maximum time frame the project could have before construction could begin, and the techniques effectivity to limit further spreading of the heavy metals. The alternative deemed valid to investigate further were to clean the hazardous fine fraction using on-site mobile soil washing.

Through LCA, three different scenarios were modelled and investigated in EASETECH: Scenario 1 consisting of landfilling the hazardous fine fraction, Scenario 2 which consisted of encapsulating the hazardous fine fraction inside a noise barrier without pre-treatment as a containment/barrier solution, and Scenario 3 which combined the cleaning of the fine fraction via mobile on-situ soil wash with encapsulation of the cleaned soil and landfilling the hazardous waste material resulting from the soil washing process. An economic analysis which was constructed through the basics of a LCC analysis were conducted when the LCA were finalized to determine the most cost-effective solution.

To encapsulate the hazardous fine fraction using barrier technology constructed as an in-situ noise barrier in Scenario 2, fully excluding the need for ex-situ transportation and treatment, are according to the LCA and economic analysis results the most viable solution, compared to the traditional way of excavating and landfilling in Scenario 1, and remediating the soil using mobile soil washing in Scenario 3. However, the high uncertainties related to leachate of the noise barrier, the noise barriers organic structure, relatively high annual precipitations in the area, and excluded environmental costs makes the solution a highly uncertain option for the future. Further investigation should be made on the potential costs of handling and monitoring the uncollected leachate from the noise barrier, and whether it can be effectivized further using a leachate collection system or a more long-term remediation technique such as phytoremediation, in order to mitigate the negative impacts related to terrestrial, marinal and freshwater eutrophication and ecotoxicity.

These results further showed the least environmental and human health impact across all chosen LCIA impact categories for Scenario 2 in comparison to Scenario 1 and Scenario 3 except ecotoxicity in freshwater. The ecotoxicity in freshwater results from Scenario 2 were higher by 33.60 CTUe compared to Scenario 1, and 7.60 CTUe compared to Scenario 3. This elevation in ecotoxicity were mainly because of uncollected leachate from the hazardous and non-hazardous material inside the noise barrier. However, as the freshwater ecotoxicity results from 10000 Monte Carlo simulations showed that Scenario 2 only were in 59.80% of the cases higher than Scenario 1, and in 51.70% of the cases higher than Scenario 3. This shows that the mitigation from cleaning the hazardous soil before encapsulating it plays a miniscule difference. It should be noted that the uncollected leachate plays a key role in the total freshwater ecotoxicity impact of Scenario 2 and Scenario 3, where 64.7% of the total impact comes from the hazardous uncollected leachate in Scenario 2, and 57.5% in Scenario 3.

The uncertainty of the parameters used for the models noise barrier leachate may however have fluctuated the results, as the variation of the 10000 Monte Carlo simulation results were high for each scenario freshwater ecotoxicity impact. This resulted in a higher spread between the results, with higher uncertainty. It was also assumed that the leachate parameters for all heavy metals were the same in all scenarios, meaning that although the heavy metal levels of the fine fraction got reduced below FA levels in Scenario 3, it still had the same leachate properties as fine fraction with heavy metal levels above FA, which in reality might be incorrect. Although these leachate parameters were primary data gathered from lab measurements of soil gathered from the site, the differences between the As and Zn leachate lab results were high, which resulted in a higher uncertainty in its mean values. As the heavy metal leachate from this solution could be problematic for the future, further research should be made with less fluctuating parameters.

Scenario 2 were also proven to be the most cost beneficial of the scenarios, in terms of handling and remediating the fine fraction, lowering the total economic impact of the project, as it would cost Skellefteå municipality approximately 222.83 SEK/tonne, compared to 2437.34 SEK/tonne in Scenario 1, and 1169.65 SEK/tonne in Scenario 3. However, as the long-term impacts of encapsulating hazardous soil inside an organic noise barrier in a sub-arctic climate are uncertain, the uncollected leachate might have higher negative impacts to the municipal economy. Higher costs related to handling and monitoring the uncollected leachate, as well as potential reconstruction and maintenance of the noise barrier in the future, could reduce the viability of the solution significantly.

The investigated alternative technique, mobile on-site soil washing is however a solution that has been used historically in other parts of the world and has a lot of potential as a solution to large-scale soil remediation. It may be a viable option for this project when it comes to the heterogenous properties of the contaminants in the soil, the volume that needs to be remediated, and considering the relatively short time availability before the construction of the industrial compound are to begin. However, due to the environmental and human health impacts caused by the estimated usage of fuel and energy to clean this large-scale and highly heavy metal contaminated soil, connected with the uncertainties of its effectivity for this scale and type of a project, the negatives outweigh the positives, as the potential risk of increased ozone depletion is higher for the solution in comparison to the solutions of Scenario 1 and Scenario 2. Scenario 3 should however be refined further before any conclusion can be made regarding the feasibility of mobile on-site soil washing, due to the high uncertainties related to the parameters included and excluded from the models process such as water, electricity and washing agents. This includes gathering more robust site-specific and primary data from local electricity producers, and mobile on-site soil washing service providers near the area.

7 SUGGESTIONS FOR FURTHER WORK

In 2019, Tyréns AB and Sweco concluded that constructing and operating a landfill at the location to handle contaminated soil waste could be a possibility, as the location had excess surface areas that could be used. This would remove the need for soil waste transportation to the Dåva landfill in Umeå, potentially limiting the environmental impact (Geisler, 2025, p. 10). However, due to time constraints, and the need for environmental permits to construct this type of landfill, (J. Wellenius & O. Rydlinge, personal communication, March 24, 2026) the solution were not plausible for this cause and thus excluded from further investigation. The solution could potentially be viable for the future however, as limits above MKM have been measured at areas outside of Näsudden. It could thus potentially be a need for a more local way of handling and depositing contaminated soil waste in the future. Another option would be to construct a treatment plant at a local waste handling facility, which could be used to sell cleaned soil and to remediate excavated soil from smaller-scale excavations. A more local solution could be beneficial environmentally, economically and socially in the long term, as more soil can be treated locally, reducing transportation costs, benefiting the local economy and the habitants of Skellefteå. The transportation of hazardous soil waste could potentially be effectivized further as well, instead of transporting by using trucks. Further research should thus be made in other modes of transportation, such as utilizing marinal- or railway transportation.

Due to the uncertainties related to the uncollected leachate from the noise barrier, further investigation should be done in effectivizing it further. This could be done by installing a leachate collection system, to be able to mitigate the leaching and potentially remove it. Utilizing another remediation technique in combination with the noise barrier encapsulation could also potentially lower the long-term risks and impacts from the high heavy metal levels inside the barrier. Alternative remediation techniques that may be worth investigating are the usage of phytoremediation, and if, for example plants or fungi can be used to extract the heavy metals. These solutions should however be tested on a pilot scale beforehand, to determine the effectivity and feasibility.

If mobile soil washing is to be used, different soil washing agents and chemicals, and their effectivity in cleaning large-scale soil structures with hazardous levels of As, Cu, Pb and Zn, as well as the reusability of the cleaned soil in-situ. If the destruction of organic soil structures, and only using strong inorganic acids for the soil washing process is prohibited, there are case studies of similar heterogenous heavy metal contamination where redox agents have been combined with EDTA (Kim et al., 2016, p. 281). For example, in their study on combining redox agents with EDTA to extract As and heavy metals from contaminated soil, Kim et al. (2016, pp. 274–278)) reached increased extraction of As, Cu, Pb and Zn using sodium dithionite ($Na_2S_2O_4$) and EDTA, compared to only using EDTA. Further investigation on the process should also be made with stronger site-specific and primary parameters related to water and electricity usage of mobile-soil washing, as well as the overall impacts of production and usage of washing agents in soil washing 100000 tonnes of hazardous fine fraction as the chosen washing agents for this study were excluded from modelling the soil washing process in Scenario 3.

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APPENDIX 1: FULL SCENARIO MODELS IN EASETECH

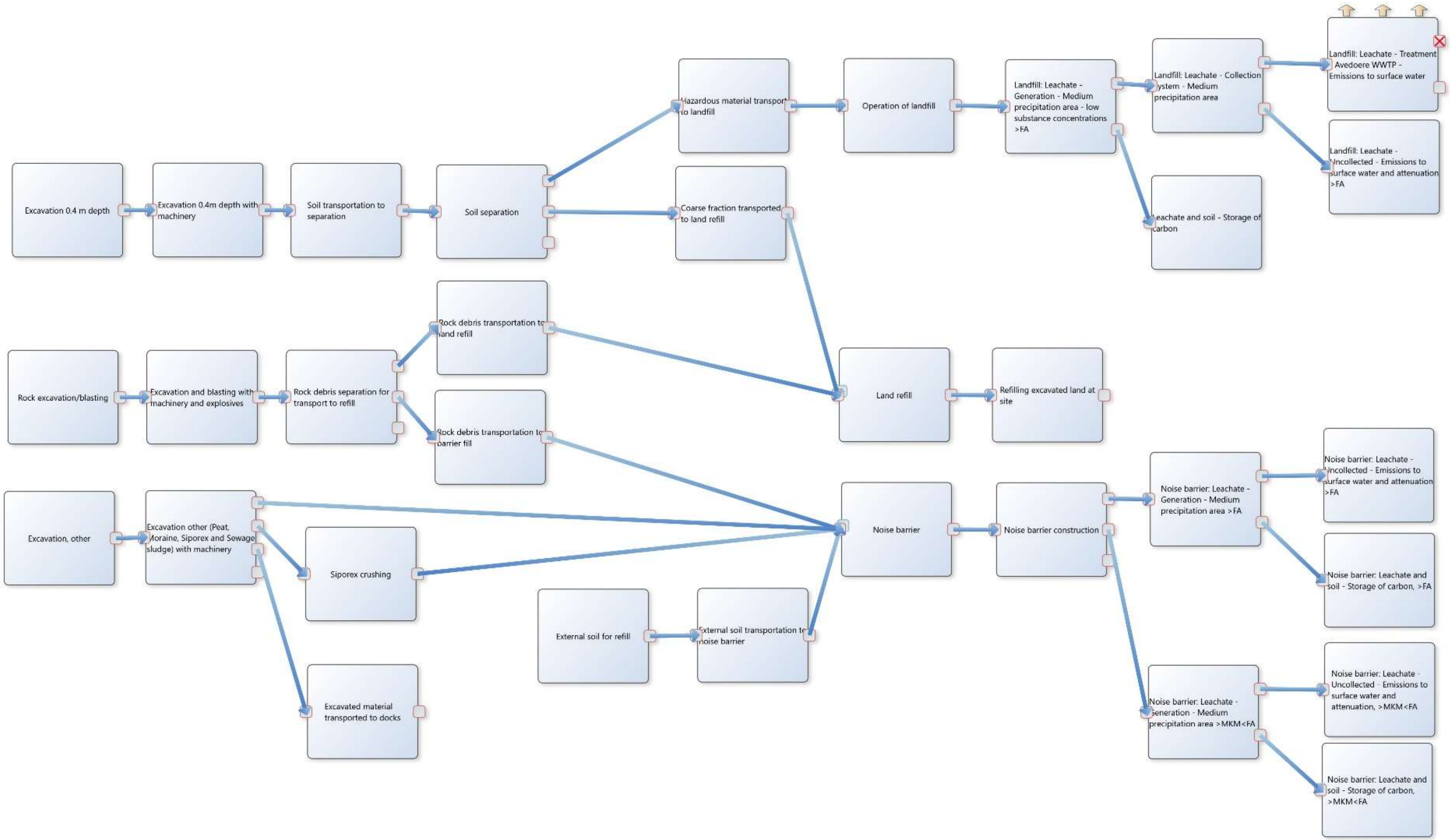

Figure 24: Full model of Scenario 1 in EASETECH consisting of all processes and flows without grouping.

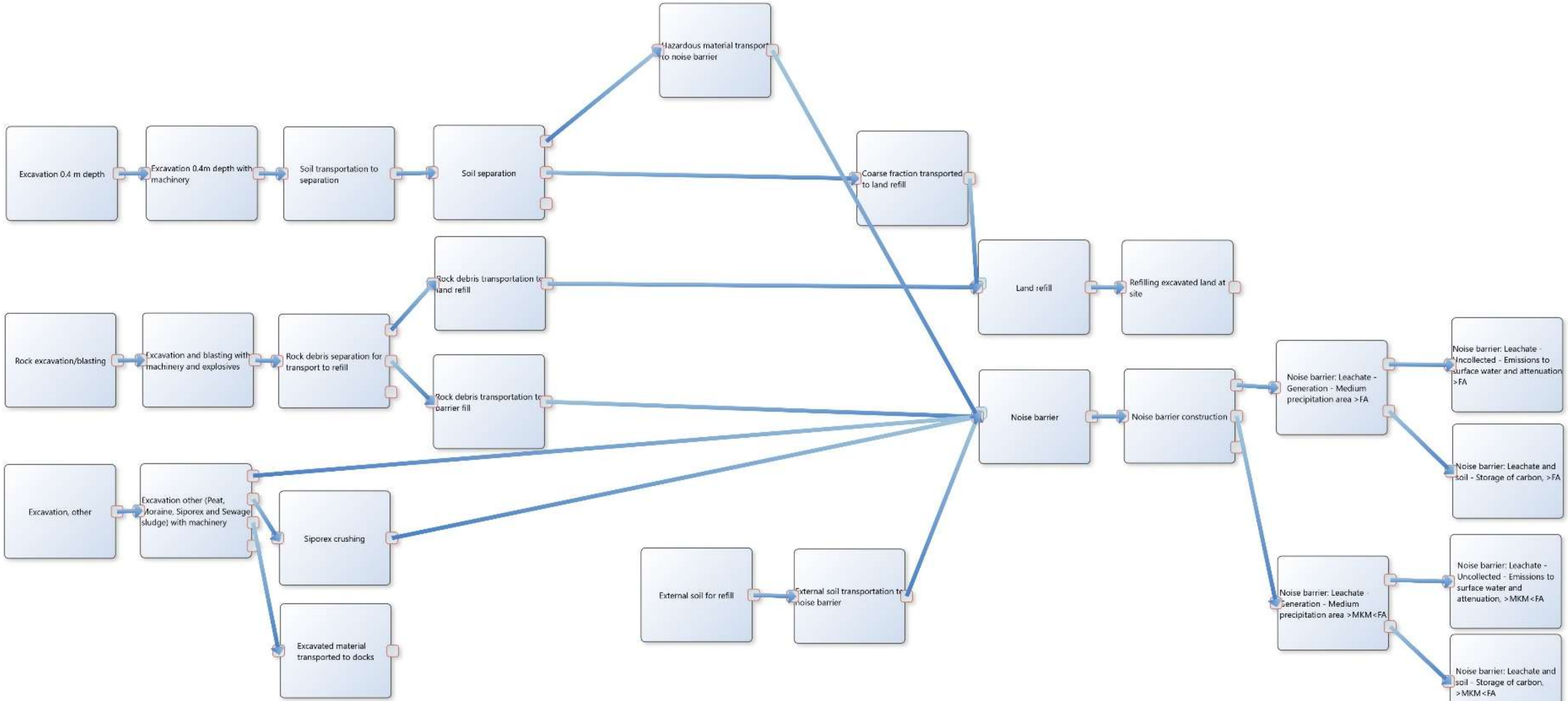

Figure 25: Full model of Scenario 2 in EASETECH consisting of all processes and flows without grouping.

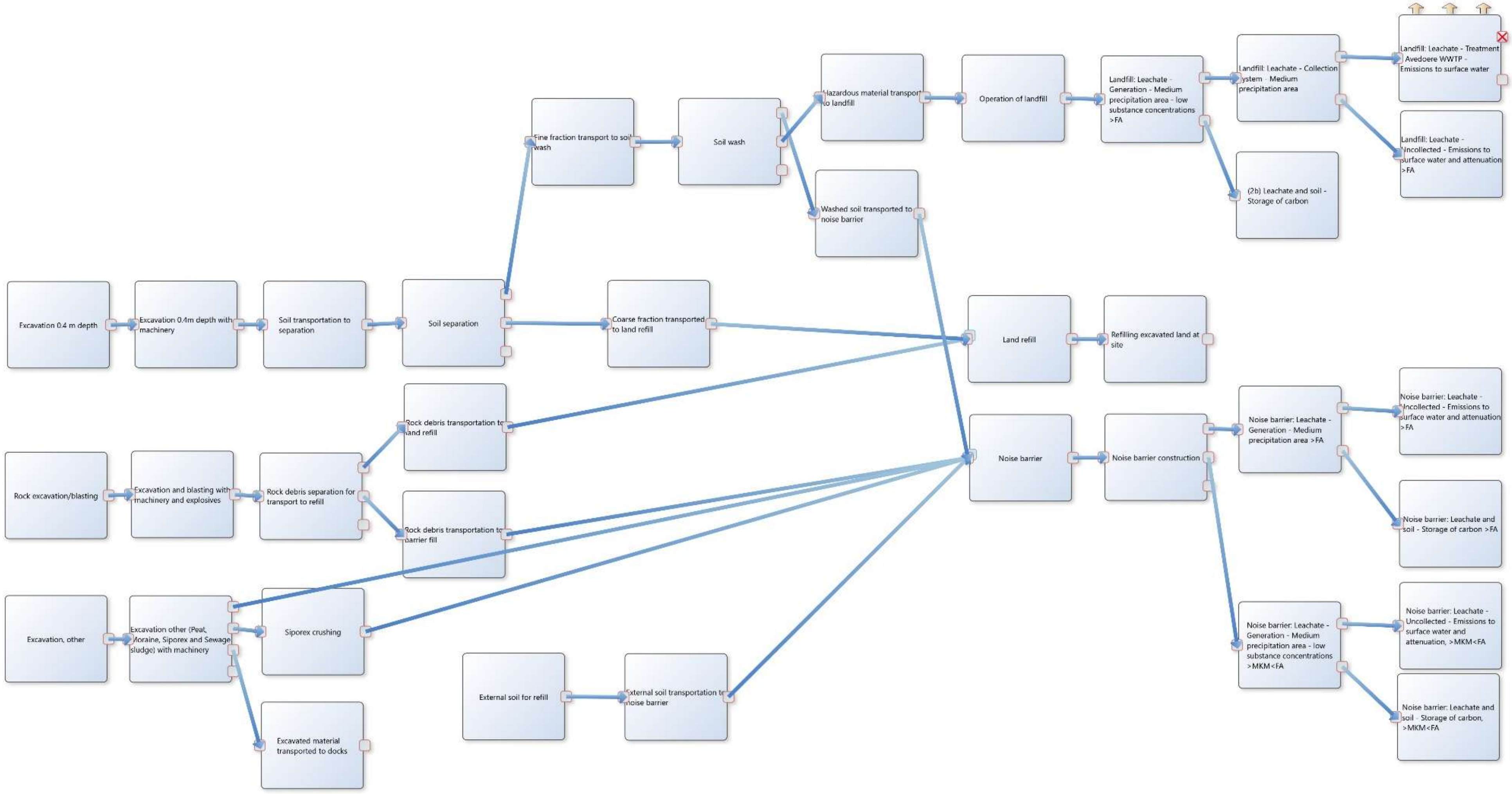

Figure 26: Full model of Scenario 3 in EASETECH consisting of all processes and flows without grouping.

APPENDIX 2: MACHINERY FUEL CONSUMPTION

The fuel consumption parameters were based on the input needed to conduct the modelling within EASETECH. The following equations are thus mostly based on assumptions to reach the needed input variables using gathered parameters.

Machinery where fuel consumption was given as litres per cubic meter (L/m3), such as Excavator, Wheel loader, and Bulldozer were converted to L/kg ($Fuel\ consumption_{per\ weight}$) by Equation 11, based on the noted correlation between load factor, soil density and volume (Trani et al., 2016, pp. 3802–3804)

$$Fuel\ consumption_{per\ weight} = \frac{Fuel\ consumption_{per\ cubic\ meter}}{\rho_{excavated\ soil}}$$

Equation 11

Where $Fuel\ consumption_{per\ cubic\ meter}$ (L/m3) is defined by the fuel consumption per volume soil, and $\rho_{excavated\ soil}$ (kg/m3) by the density of the excavated soil, based on the density of the fine- and coarse fraction. The same $Fuel\ consumption_{per\ weigh}$ (L/kg) were assumed for all excavation points disregarding the heterogeneity of the soil structures outside the 0.4 m depth excavation point.

The dumpers fuel consumption, $Fuel\ consumption_{dumper}$ (L/kg) was assumed to be based on the dumper fuel consumption in MJ/tkm, an estimated travel length, and the diesel engine of the dumper (Göteborgs stad, 2025; Trafikverket & Skanska, 2025), calculated by Equation 12.

$$Fuel\ consumption_{dumper} = \frac{Fuel\ consumption_{dumper,\frac{MJ}{tkm}} * HHV_{inverted,diesel}}{d_{dumper,transportation}}$$

Equation 12

Where $Fuel\ consumption_{dumper,MJ/tkm}$ where given in MJ/tkm, $HHV_{inverted,diesel}$ (L/MJ) the inverted higher heating value of diesel, and $d_{dumper,transportation}$ by an overall assumed transportation distance per transport of 0.3 km.

The fuel consumption of the drill rig, $Fuel\ consumption_{drill\ rig}$ (L/kg) were determined by Equation 13 (Göteborgs stad, 2025).

$$Fuel\ consumption_{drill\ rig} = \frac{(Energy\ consumption_{drill\ rig} * HHV_{inverted,diesel})}{\rho_{excavated\ rocks}}$$

Equation 13

Where $Energy\ consumption_{drill\ rig}$ (MJ/m3) is defined by the energy consumption per volume of the drill rig $HHV_{inverted,diesel}$ (L/MJ) the inverted higher heating value of diesel, and $\rho_{excavated\ rocks}$ (kg/m³) by the density of the rock mountains that are to be excavated and blasted.

The fuel consumption for the separator $Fuel\ consumption_{separator}$ (L/kg) were determined by Equation 14.

$$Fuel\ consumption_{separator} = 2 * Performance_{separator} * Fuel\ consumption_{separator,per\ h} \quad \text{Equation 14}$$

Where $Performance_{separator}$ (tonnes/h) were defined by the production performance of the separator, where two separators are running at the same time, and $Fuel\ consumption_{separator,per\ h}$ (L/h) by the diesel fuel consumption per hour of one separator.

Fuel consumption by trucks for hazardous waste transportation, and external soil delivery, $Fuel\ consumption_{truck}$ (kg*km/kg) where determined by Equation 15.

$$Fuel\ consumption_{truck} = \frac{m_{transported} * d_{truck,transportation}}{m_{transported}} = d_{truck,transportation} \quad \text{Equation 15}$$

Where $m_{transported}$ (kg) is defined by the weight of the transported soil or waste, and $d_{truck,transportation}$ (km) by the one-way distance of the truck transportation, based on transportation from Näsudden to Dåva, Umeå, and from Luleå to Näsudden (Google, 2026; M. Lindmark, personal communication, March 26, 2026; Norrlandsjord & Miljö AB, 2026a).

APPENDIX 3: PEDIGREE MATRIX

Table 30: Pedigree matrix used in LCI for data quality assessment with scoring of 0-5 for GR, TeR, TiR, P, C, Xw and i to calculate DQR, Time Period for the year of the data parameter, References and classifying the parameter as Primary or Secondary.

	Parameter	Variable	Unit	Geographical representitaveness (GR)	Technological representativeness (TeR)	Time-related representativeness (TiR)	Reliability (P)	Completeness (C)	Weakest quality level (Xw)	Number of applicable data quality indicators (i)	DQR	Time period	Reference(s)	Prim/Sec
SOIL AND EARTH FRACTIONS	Total Soil that needs to be excavated	600000	m3	1	1	1	2	2	2	5	1.7	2025	(Sweco, 2025a, p. 23)	Primary
	Soil that needs to be excavated (0.4m depth)	270000	m3	1	1	1	2	2	2	5	1.7	2025	(Geisler, 2025, p. 20)	Primary
	Soil that needs to be excavated (0.4m depth)	500000	ton	1	1	1	3	2	3	5	2.2	2025	(Geisler, 2025, p. 22)	Primary
	Calculated density of soil according to literature (assumed same for fine and coarse fraction)	1851.851852	kg/m3	1	1	1	3	2	3	5	2.2	2025	(Geisler, 2025, p. 22)	Primary
	External topsoil needed (matjord) volume	25043	m3	1	1	1	3	3	3	5	2.3	2025	(Geisler, 2025, pp. 20–22 & pp. 43–45; M. Lindmark, personal communication, March 26, 2026).	Primary
	External topsoil (matjord) density	1600	kg/m3	2	2	1	3	1	3	5	2.3	2026	(Snabbgrus, 2026; Y-Kross AB, 2026).	Secondary

External topsoil needed (matjord) weight	40068800	kg	2	2	1	3	2	3	5	2.4	2025-2026	(Geisler, 2025, pp. 20–22 & pp. 43–45; M. Lindmark, personal communication, March 26, 2026; Snabbgrus, 2026; Y-Kross AB, 2026).	Secondary
External topsoil needed (matjord) weight, including replacement for fine fraction	140068800	kg	2	2	1	4	2	4	5	3.0	2025-2026	(Geisler, 2025, pp. 20–22 & pp. 43–45; M. Lindmark, personal communication, March 26, 2026; Snabbgrus, 2026; Y-Kross AB, 2026).	Secondary
Fine fraction volume	54000	m3	1	1	1	2	2	2	5	1.7	2025	(Geisler, 2025, p. 22)	Primary
Coarse fraction volume	216000	m3	1	1	1	2	2	2	5	1.7	2025	(Geisler, 2025, p. 22)	Primary
Excavation, other weight	685641	ton	1	1	1	3	1	3	5	2.1	2025	(Geisler, 2025, p. 22)	Primary
Fine fraction contaminated soil waste that needs to be remediated/deposited	100000	ton	1	1	1	2	1	2	5	1.6	2025	(Geisler, 2025, p. 22)	Primary
Coarse fraction weight	400000	ton	1	1	1	3	2	3	5	2.2	2025	(Geisler, 2025, p. 22)	Primary
Soil that does not need to be remediated/deposited	400000	ton	1	1	1	2	1	2	5	1.6	2025	(Geisler, 2025, p. 14; Geisler, 2025, p. 22)	Primary
Fine fraction TS	37400	ton	1	1	2	2	1	2	5	1.7	2022-2025	(Geisler, 2025, p. 22; Afry, 2022)	Primary
Fine fraction TS	37400000	kg	1	1	2	2	1	2	5	1.7	2022-2025	(Geisler, 2025, p. 22; Afry, 2022)	Primary
Coarse fraction TS	347200	ton	1	1	2	2	1	2	5	1.7	2022-2025	(Geisler, 2025, p. 14; Geisler, 2025, p. 22; Afry, 2022)	Primary

Coarse fraction TS	130200000	kg	1	1	2	2	1	2	5	1.7	2022-2025	(Geisler, 2025, p. 14; Geisler, 2025, p. 22; Afry, 2022)	Primary
Fiine fraction %	40	%	1	1	1	2	2	2	5	1.7	2025	(Geisler, 2025, p. 14; Geisler, 2025, p. 22)	Primary
Coarse fraction %	60	%	1	1	1	2	2	2	5	1.7	2025	(Geisler, 2025, p. 14; Geisler, 2025, p. 22)	Primary
Rock mountains excavated	1200000	m3	1	1	1	3	2	3	5	2.2	2025	(Sweco, 2025a, pp. 21–22)	Primary
Rock mountains excavated	3240000000	kg	1	1	1	3	2	3	5	2.2	2025	(Sweco, 2025a, pp. 21–22)	Primary
Rock mountains density	2700	kg/m3	1	1	1	3	2	3	5	2.2	2025	(Sweco, 2025a, pp. 21–22)	Primary
Rock debris needed for noise barrier, total volume	21413	m3	1	1	1	2	1	2	5	1.6	2025	(Geisler, 2025, p. 43)	Primary
Rock debris needed for land refill (above terrace)	965000	m3	1	1	1	2	1	2	5	1.6	2025	(Geisler, 2025, p. 20)	Primary
Rock debris needed for noise barrier in %	2.170794586	%	1	1	1	3	1	3	5	2.1	2025	(Geisler, 2025, p. 43)	Primary
Material needed for noise barrier	440000	m3	1	1	1	2	2	2	5	1.7	2025	(Sweco, 2025a, pp. 22–23)	Primary
Material needed for land refill	210000	m3	1	1	1	2	2	2	5	1.7	2025	(Geisler, 2025, p. 20)	Primary
Fine fraction %TS (AVERAGE)	37.4	%	1	1	2	2	1	2	5	1.7	2022	(Afry, 2022)	Primary
Fine fraction %Water (AVERAGE)	62.6	%	1	1	2	2	1	2	5	1.7	2022	(Afry, 2022)	Primary
Fine fraction TOC %TS (AVERAGE)	38.25	%	1	1	2	2	1	2	5	1.7	2022	(Afry, 2022)	Primary
Coarse fraction %TS (AVERAGE)	86.8	%	1	1	2	2	1	2	5	1.7	2022	(Afry, 2022)	Primary
Coarse fraction %Water (AVERAGE)	13.2	%	1	1	2	2	1	2	5	1.7	2022	(Afry, 2022)	Primary
Coarse fraction TOC %TS (AVERAGE)	1.4425	%	1	1	2	2	1	2	5	1.7	2022	(Afry, 2022)	Primary
Peat %water, %TS and %TS levels for all contaminants	Same as fine fraction	%	1	1	2	4	3	4	5	3.0	2022	(Afry, 2022; Geisler, 2025, pp. 20–22)	Primary

	Moraine and Siporex %water, %TS and %TS levels for all contaminants	Same as coarse fraction	%	1	1	2	5	3	5	5	3.6	2022, 2025	(Afry, 2022; Geisler, 2025, pp. 20–22)	Primary
	Sewage sludge %water, %TS, %VS, %Ash	90, 10, 80, 20	%	2	1	3	1	2	3	5	2.3	2016	(Technical University of Denmark, 2026)	Secondary
	Sewage sludge %water, %TS and %TS levels for all contaminants	Same as coarse fraction and Database %Water and %TS	%	1	1	2	5	3	5	5	3.6	2022, 2025	(Afry, 2022; Geisler, 2025, pp. 20–22)	Secondary

CONTAMINANTS	As	46	ton	1	1	1	1	1	1	5	1.0	2025	(Sweco, 2025b, p. 14; Vendt & Paulsson, 2025, p. 5)	Primary
	As: Fine fraction mean (mg/kg)	1781.25	mg/kg TS	1	1	2	1	1	2	5	1.6	2022	(Afry, 2022)	Primary
	As: Fine fraction %TS	0.178125	%TS	1	1	2	2	0	2	4	1.8	2022 and 2025	(Afry, 2022) (Geisler, 2025, p. 22)	Primary
	As: Coarse fraction mean (mg/kg)	169.75	mg/kg TS	1	1	2	1	1	2	5	1.6	2022	(Afry, 2022)	Primary
	As: Coarse fraction %TS	0.016975	%TS	1	1	2	2	0	2	4	1.8	2022	(Afry, 2022; Geisler, 2025, p. 14; Geisler, 2025, p. 22)	Primary
	Cu	63	ton	1	1	1	1	1	1	5	1.0	2025	(Sweco, 2025b, p. 14)	Primary
	Cu: Fine fraction mean (mg/kg)	5287.50	mg/kg TS	1	1	2	1	1	2	5	1.6	2022	(Afry, 2022)	Primary
	Cu: Fine fraction %TS	0.52875	%	1	1	2	2	0	2	4	1.8	2022 and 2025	(Afry, 2022; Geisler, 2025, p. 22)	Primary
	Cu: Coarse fraction mean (mg/kg)	75.00	mg/kg TS	1	1	2	1	1	2	5	1.6	2022	(Afry, 2022)	Primary

	Cu: Coarse fraction %TS	0.0075	%	1	1	2	2	0	2	4	1.8	2022	(Afry, 2022; Geisler, 2025, p. 14; Geisler, 2025, p. 22)	Primary
	Hg	500	ton	1	1	1	1	1	1	5	1.0	2025	(Sweco, 2025b, p. 14; Vendt & Paulsson, 2025, p. 5)	Primary
	Hg: Fine fraction mean (mg/kg)	21.25	mg/kg TS	1	1	2	1	1	2	5	1.6	2022	(Afry, 2022)	Primary
	Hg: Fine fraction %TS	0.002125	%	1	1	2	2	0	2	4	1.8	2022 and 2025	(Afry, 2022; Geisler, 2025, p. 22)	Primary
	Hg: Coarse fraction mean (mg/kg)	0.10	mg/kg TS	1	1	2	1	1	2	5	1.6	2022	(Afry, 2022)	Primary
	Hg: Coarse fraction %TS	9.8125E-06	%	1	1	2	2	0	2	4	1.8	2022	(Afry, 2022; Geisler, 2025, p. 14; Geisler, 2025, p. 22)	Primary
	Pb	90	ton	1	1	1	1	1	1	5	1.0	2025	(Sweco, 2025b, p. 14; Vendt & Paulsson, 2025, p. 5)	Primary
	Pb: Fine fraction mean (mg/kg)	10287.50	mg/kg TS	1	1	2	1	1	2	5	1.6	2022	(Afry, 2022)	Primary
	Pb: Fine fraction %TS	1.02875	%	1	1	2	2	0	2	4	1.8	2022 and 2025	(Afry, 2022; Geisler, 2025, p. 22)	Primary
	Pb: Coarse fraction mean (mg/kg)	72.41	mg/kg TS	1	1	2	1	1	2	5	1.6	2022	(Afry, 2022)	Primary
	Pb: Coarse fraction %TS	0.00724125	%	1	1	2	2	0	2	4	1.8	2022	(Afry, 2022; Geisler, 2025, p. 14; Geisler, 2025, p. 22)	Primary
	Zn	42	ton	1	1	1	2	1	2	5	1.6	2025	(Sweco, 2025b, p. 14)	Primary
	Zn: Fine fraction mean (mg/kg)	2472.50	mg/kg TS	1	1	2	1	1	2	5	1.6	2022	(Afry, 2022)	Primary
	Zn: Fine fraction %TS	0.24725	%	1	1	2	2	0	2	4	1.8	2022	(Afry, 2022; Geisler, 2025, p. 22)	Primary

	Zn: Coarse fraction mean (mg/kg)	79.38	mg/kg TS	1	1	2	1	1	2	5	1.6	2022	(Afry, 2022)	Primary
	Zn: Coarse fraction %TS	0.0079375	%	1	1	2	2	0	2	4	1.8	2022	(Afry, 2022; Geisler, 2025, p. 14; Geisler, 2025, p. 22)	Primary
	Ba: Fine fraction mean (mg/kg)	253.75	mg/kg TS	1	1	2	1	1	2	5	1.6	2022	(Afry, 2022)	Primary
	Ba: Fine fraction %TS	0.025375	%	1	1	2	2	0	2	4	1.8	2022	(Afry, 2022; Geisler, 2025, p. 22)	Primary
	Ba: Coarse fraction mean (mg/kg)	31.63	mg/kg TS	1	1	2	1	1	2	5	1.6	2022	(Afry, 2022)	Primary
	Ba: Coarse fraction %TS	0.0031625	%	1	1	2	2	0	2	4	1.8	2022	(Afry, 2022; Geisler, 2025, p. 14; Geisler, 2025, p. 22)	Primary
	Cd: Fine fraction mean (mg/kg)	27.00	mg/kg TS	1	1	2	1	1	2	5	1.6	2022	(Afry, 2022)	Primary
	Cd: Fine fraction %TS	0.0027	%	1	1	2	2	0	2	4	1.8	2022	(Afry, 2022; Geisler, 2025, p. 22)	Primary
	Cd: Coarse fraction mean (mg/kg)	1.21	mg/kg TS	1	1	2	1	1	2	5	1.6	2022	(Afry, 2022)	Primary
	Cd: Coarse fraction %TS	0.000121375	%	1	1	2	2	0	2	4	1.8	2022	(Afry, 2022; Geisler, 2025, p. 14; Geisler, 2025, p. 22)	Primary
	Co: Fine fraction mean (mg/kg)	10.65	mg/kg TS	1	1	2	1	1	2	5	1.6	2022	(Afry, 2022)	Primary
	Co: Fine fraction %TS	0.001065	%	1	1	2	2	0	2	4	1.8	2022	(Afry, 2022; Geisler, 2025, p. 22)	Primary
	Co: Coarse fraction mean (mg/kg)	2.83	mg/kg TS	1	1	2	1	1	2	5	1.6	2022	(Afry, 2022)	Primary
	Co: Coarse fraction %TS	0.0002825	%	1	1	2	2	0	2	4	1.8	2022	(Afry, 2022; Geisler, 2025, p. 14; Geisler, 2025, p. 22)	Primary

	Ni: Fine fraction mean (mg/kg)	69.13	mg/kg TS	1	1	2	1	1	2	5	1.6	2022	(Afry, 2022)	Primary
	Ni: Fine fraction %TS	0.0069125	%	1	1	2	2	0	2	4	1.8	2022	(Afry, 2022; Geisler, 2025, p. 22)	Primary
	Ni: Coarse fraction mean (mg/kg)	3.44	mg/kg TS	1	1	2	1	1	2	5	1.6	2022	(Afry, 2022)	Primary
	Ni: Coarse fraction %TS	0.00034375	%	1	1	2	2	0	2	4	1.8	2022	(Afry, 2022; Geisler, 2025, p. 14; Geisler, 2025, p. 22)	Primary
	V: Fine fraction mean (mg/kg)	983.75	mg/kg TS	1	1	2	1	1	2	5	1.6	2022	(Afry, 2022)	Primary
	V: Fine fraction %TS	0.098375	%	1	1	2	2	0	2	4	1.8	2022	(Afry, 2022; Geisler, 2025, p. 22)	Primary
	V: Coarse fraction mean (mg/kg)	23.88	mg/kg TS	1	1	2	1	1	2	5	1.6	2022	(Afry, 2022)	Primary
	V: Coarse fraction %TS	0.0023875	%	1	1	2	2	0	2	4	1.8	2022	(Afry, 2022; Geisler, 2025, p. 14; Geisler, 2025, p. 22)	Primary

LEACHING	As: Fine fraction Leaching mean	0.241361219	mg/kg TS	1	1	2	2	1	2	5	1.7	2022	(Afry, 2022)	Primary
	Cu: Fine fraction Leaching mean	0.278874523	mg/kg TS	1	1	2	2	1	2	5	1.7	2023	(Afry, 2022)	Primary
	Pb: Fine fraction Leaching mean	0.077279282	mg/kg TS	1	1	2	2	1	2	5	1.7	2024	(Afry, 2022)	Primary
	Zn: Fine fraction Leaching mean	0.762374168	mg/kg TS	1	1	2	2	1	2	5	1.7	2025	(Afry, 2022)	Primary
	As: Coarse fraction Leaching mean	0.122643412	mg/kg TS	1	1	2	2	1	2	5	1.7	2025	(Afry, 2022)	Primary
	Cu: Coarse fraction Leaching mean	0.024124961	mg/kg TS	1	1	2	2	1	2	5	1.7	2025	(Afry, 2022)	Primary
	Pb: Coarse fraction Leaching mean	0.007186508	mg/kg TS	1	1	2	2	1	2	5	1.7	2025	(Afry, 2022)	Primary
	Zn: Coarse fraction Leaching mean	0.006223046	mg/kg TS	1	1	2	2	1	2	5	1.7	2025	(Afry, 2022)	Primary

	As: Peat Leaching mean	0.241361219	mg/kg TS	1	1	2	4	1	4	5	2.8	2022	(Afry, 2022)	Primary
	Cu: Peat fraction Leaching mean	0.278874523	mg/kg TS	1	1	2	4	1	4	5	2.8	2023	(Afry, 2022)	Primary
	Pb: Peat fraction Leaching mean	0.077279282	mg/kg TS	1	1	2	4	1	4	5	2.8	2024	(Afry, 2022)	Primary
	Zn: Peat fraction Leaching mean	0.762374168	mg/kg TS	1	1	2	4	1	4	5	2.8	2025	(Afry, 2022)	Primary
	As: Moraine, Siporex, Rock debris, Sewage sludge fraction Leaching mean	0.122643412	mg/kg TS	1	1	2	5	1	5	5	3.3	2025	(Afry, 2022)	Primary
	Cu: Moraine, Siporex, Rock debris, Sewage sludge fraction Leaching mean	0.024124961	mg/kg TS	1	1	2	5	1	5	5	3.3	2025	(Afry, 2022)	Primary
	Pb: Moraine, Siporex, Rock debris, Sewage sludge fraction Leaching mean	0.007186508	mg/kg TS	1	1	2	5	1	5	5	3.3	2025	(Afry, 2022)	Primary
	Zn: Moraine, Siporex, Rock debris, Sewage sludge fraction Leaching mean	0.006223046	mg/kg TS	1	1	2	5	1	5	5	3.3	2025	(Afry, 2022)	Primary
	Precipitation (Avg 2022-2024)	493.8666667	mm/year	2	1	1	1	1	2	5	1.6	2022-2024	(SMHI, 2026)	Secondary
MACHINERY	Truck transport from excavation to Dåva landfill, Umeå (Truck, 28t-32t, Euro6, highway)	12000000000	kg*km	3	3	1	3	3	3	5	2.8	2025	(Geisler, 2025, p. 14; Geisler, 2025, p. 24) & Assumption	Primary
	Truck transport from Luleå to Näsudden (Truck, 28t-32t, Euro6, highway)	14000000000	kg*km	3	3	1	3	3	3	5	2.8	2026	(Google, 2026; M. Lindmark, personal communication, March 26, 2026)	Secondary
	Separator (RM HS5000M cummins stage5) capacity x2	660	ton/h	3	1	1	2	1	3	5	2.2	2026	(RM Group, n.d., p. 9)	Secondary
	Hours needed for separation (fine fraction and coarse fraction)	378.7878788	h	0	1	2	3	2	3	4	2.5	2025, 2026	(RM Group, n.d., p. 9; Geisler, 2025, p. 22)	Secondary

Separator (RM HS5000M cummins stage5) fuel consumption (diesel) per h	20	L/h	3	1	1	4	2	4	5	3.0	2026	(Representative RUBBLE MASTER HMH GmbH, personal communication, April 7, 2026)	Secondary
Separator (RM HS5000M cummins stage5) fuel consumption (diesel) per kg	1.51515E-05	L/kg	3	1	2	4	2	4	5	3.1	2025, 2026	(Representative RUBBLE MASTER HMH GmbH, personal communication, April 7, 2026; RM Group, n.d., p. 9; Geisler, 2025, p. 22)	Secondary
Explosives needed for rock blasting (Tovex) (HARD ROCK)	0.00037	kg/kg	3	2	1	1	3	3	5	2.4	2023	(De Bortoli, 2023, p. 7)	Secondary
Dumper fuel consumption (Diesel)	6.27	MJ/tkm	3	1	1	1	1	3	5	2.1	2025	(Trafikverket & Skanska, 2025)	Secondary
Inverted Diesel MK1 Energy heating value	0.028345	L/MJ	3	1	1	1	1	3	5	2.1	2025	(Göteborgs stad, 2025; Trafikverket & Skanska, 2025)	Secondary
Dumper fuel consumption (Diesel) based on 0.3 km drive	5.33169E-05	L/kg	3	2	1	4	3	4	5	3.2	2025	(Göteborgs stad, 2025; Trafikverket & Skanska, 2025)	Secondary
Wheel loader (small), bucket load	1.9	m3	3	2	3	2	1	3	5	2.6	2016	(Trani et al., 2016, p. 3807)	Secondary
Wheel loader (small) productivity rate	0.008	h/m3	3	2	3	2	1	3	5	2.6	2016	(Trani et al., 2016, p. 3807)	Secondary
Wheel loader (small) fuel consumption (L/m3)	0.04	L/m3	3	2	3	2	1	3	5	2.6	2016	(Trani et al., 2016, p. 3807)	Secondary
Wheel loader (small) fuel consumption (L/kg)	0.0000216	L/kg	3	3	2	3	3	3	5	2.9	2016	(Trani et al., 2016, p. 3807; Geisler, 2025, p. 22)	Secondary
Excavator fuel consumption (L/m3)	0.0001026	L/kg	3	3	1	3	3	3	5	2.8	2025	(Göteborgs stad, 2025; Trafikverket & Skanska, 2025; Geisler, 2025, p. 22)	Secondary

	Excavator fuel consumption (L/m3)	0.19	L/m3	3	3	1	3	3	3	5	2.8	2025	(Göteborgs stad, 2025; Trafikverket & Skanska, 2025; Sweco, 2025a, pp. 21–22)	Secondary
	Drill rig productivity rate	50	m3/h	3	3	4	1	1	4	5	3.1	2010	(Complicated ECE Working Group, NRAAC, 2010, p. 6)	Secondary
	Drill rig fuel consumption	2.62454E-05	L/kg	3	3	1	3	1	3	5	2.6	2025	(Göteborgs stad, 2025; Trafikverket & Skanska, 2025; Sweco, 2025a, pp. 21–22)	Secondary
	Drill rig energy consumption	2.5	MJ/m3	3	3	1	1	1	3	5	2.3	2025	(Göteborgs stad, 2025)	Secondary
	Bulldozer, Specific fuel consumption (U-blade)	0.0625	L/m3	3	3	1	1	1	3	5	2.3	2025	(Diachenko & Balaka, 2025, p. 64)	Secondary
	Bulldozer, fuel consumption (U-blade)	0.00003375	L/kg	3	3	2	3	2	3	5	2.8	2025	(Diachenko & Balaka, 2025, p. 64; Geisler, 2025, p. 22)	Secondary
	Diesel density	0.845	kg/l	2	1	1	1	1	2	5	1.6	2026	(Technical University of Denmark, 2026)	Secondary
	Diesel usage landfill	20.23	L/t	3	1	4	1	1	4	5	2.9	2010	(Iodice et al. 2021, p. 86, 2021, p. Appendix A.4)	Secondary
	Electricity usage landfill	1.14	kWh/t	3	1	4	1	1	4	5	2.9	2010	(Iodice et al. 2021, p. 86, 2021, p. Appendix A.4)	Secondary
SOIL WASH	Water usage for soil washing	0.2	kg water/kg	2	2	2	1	1	2	5	1.8	2021	(Gluhar et al., 2021, p. 6)	Secondary
	EDTA usage for soil washing	0.006	kg EDTA/kg	2	2	2	1	1	2	5	1.8	2021	(Gluhar et al., 2021, p. 6)	Secondary
	EDTA Pb removal efficiency	71.28%	%	2	2	2	1	1	2	5	1.8	2021	(Gluhar et al., 2021, p. 1)	Secondary
	EDTA Zn removal efficiency	53.00%	%	2	2	2	1	1	2	5	1.8	2021	(Gluhar et al., 2021, p. 1)	Secondary
	Phosphoric acid As removal efficiency (0.6M)	62.96%	%	3	2	2	1	3	3	5	2.6	2020	(Cho et al., 2020, p. 9)	Secondary

Sulfuric acid and Phosphoric acid mix, As removal efficiency (0.6M)	70.50%	%	3	2	2	1	3	3	5	2.6	2020	(Cho et al., 2020, p. 9)	Secondary
Sulfuric acid and Phosphoric acid mix, Cu removal efficiency (0.6M)	79.70%	%	3	2	2	1	3	3	5	2.6	2020	(Cho et al., 2020, p. 9)	Secondary
Sulfuric acid and Phosphoric acid mix, Pb removal efficiency (0.6M)	80.10%	%	3	2	2	1	3	3	5	2.6	2020	(Cho et al., 2020, p. 9)	Secondary
Sulfuric acid and Phosphoric acid mix, Zn removal efficiency (0.6M)	71.20%	%	3	2	2	1	3	3	5	2.6	2020	(Cho et al., 2020, p. 9)	Secondary
Sulfuric acid As removal efficiency (0.6M)	35.81%	%	3	2	2	1	3	3	5	2.6	2020	(Cho et al., 2020, p. 9)	Secondary
Sulfuric acid Cu removal efficiency (0.6M)	65.35%	%	3	2	2	1	3	3	5	2.6	2020	(Cho et al., 2020, p. 9)	Secondary
Sulfuric acid Pb removal efficiency (0.6M)	76.19%	%	3	2	2	1	3	3	5	2.6	2020	(Cho et al., 2020, p. 9)	Secondary
Sulfuric acid Zn removal efficiency (0.6M)	62.38%	%	3	2	2	1	3	3	5	2.6	2020	(Cho et al., 2020, p. 9)	Secondary
Hazardous waste after soil wash, mobile soil wash	15.00%	%	2	2	1	2	3	3	5	2.4	2023	(Boskalis Environmental, 2023, p. A)	Secondary
Sulfuric acid and Phosphoric acid L/S	7:1 or 7 L/kg	L/kg	3	2	2	1	3	3	5	2.6	2020	(Cho et al., 2020, pp. 7–10)	Secondary
Sulfuric acid molar weight	98.080	g/mol	0	2	1	1	1	2	4	1.6	2025	(National Center for Biotechnology Information, 2025a, 2025b)	Secondary
Phosphoric acid molar weight	97.995	g/mol	0	2	1	1	1	2	4	1.6	2025	(National Center for Biotechnology Information, 2025a, 2025b)	Secondary
Sulfuric acid washing agent per treated soil	0.411936	kg/kg	3	1	2	3	4	4	5	3.2	2020, 2025	(Cho et al., 2020, pp. 7–10; National Center for Biotechnology Information, 2025a, 2025b)	Secondary
Phosphoric acid washing agent per treated soil	0.411579	kg/kg	3	1	2	3	4	4	5	3.2	2020, 2025	(Cho et al., 2020, pp. 7–10; National Center for Biotechnology Information, 2025a, 2025b)	Secondary

Water usage for soil washing	11.42	m3/m3	3	2	2	2	3	3	5	2.7	2021	(Vocciante et al., 2021, p. 5)	Secondary
Water usage for soil washing, converted into L/kg at Näsudden	6.1668	kg/kg	3	2	2	5	3	5	5	3.9	2021 & 2025	(Vocciante et al., 2021, p. 5; Geisler, 2025, p. 22)	Secondary
Electricity usage for soil washing	23	MJ/m3	3	2	2	2	3	3	5	2.7	2021	(Vocciante et al., 2021, p. 5)	Secondary
Electricity usage for soil washing, converted into kWh/kg at Näsudden	0.00345	kWh/kg	3	2	2	5	3	5	5	3.9	2021 & 2025	(Vocciante et al., 2021, p. 5; Geisler, 2025, p. 22)	Secondary

EMISSION FACTORS	Tovex T Detonation of Explosives: CO2	1.40E-01	kg/kg	3	3	1	1	1	3	5	2.3	2022, 2023	(SSE Holding SA / SSE & The Norwegian EPD Foundation, 2022, pp. 5)	Secondary
	Tovex T Detonation of Explosives: CO	7.28E-05	kg/kg	3	3	1	1	1	3	5	2.3	2022, 2023	(SSE Holding SA / SSE & The Norwegian EPD Foundation, 2022, pp. 5)	Secondary
	Tovex T Detonation of Explosives: H2O	4.93E-01	kg/kg	3	3	1	1	1	3	5	2.3	2022, 2023	(SSE Holding SA / SSE & The Norwegian EPD Foundation, 2022, pp. 5)	Secondary
	Tovex T Detonation of Explosives: N2	2.44E-01	kg/kg	3	3	1	1	1	3	5	2.3	2022, 2023	(SSE Holding SA / SSE & The Norwegian EPD Foundation, 2022, pp. 5)	Secondary

	Tovex T Detonation of Explosives: NOx	7.34E-03	kg/kg	3	3	1	1	1	3	5	2.3	2022, 2023	(SSE Holding SA / SSE & The Norwegian EPD Foundation, 2022, pp. 5)	Secondary
	Tovex T Detonation of Explosives: Na2CO3	3.17E-20	kg/kg	3	3	1	1	1	3	5	2.3	2022, 2023	(SSE Holding SA / SSE & The Norwegian EPD Foundation, 2022, pp. 5)	Secondary

APPENDIX 4: LCIA RESULTS

Table 31: LCIA results for the chosen impact categories for Scenario 1, Scenario 2, and Scenario 3, divided into each process impact results and total results.

Process	Climate change (kg CO_2-Eq)	Ozone depletion (kg CFC-11 Eq)	Human toxicity, cancer effects (CTUh)	Human toxicity, non-cancer effects (CTUh)	Particulate matter (kgPM2.5-Eq)	Terrestrial acidification, Accumulated Exceedance (mol H+ eq.)	Eutrophic-ation Terrestrial, Accumulated Exceedance (mol N eq.)	Eutrophic-ation Freshwater (kg P eq.)	Eutrophic-ation Marine (kg N eq.)	Ecotoxicity freshwater (CTUe)
S1.Dock	3.67E-01	1.34E-10	4.71E-10	7.19E-08	6.56E-05	2.47E-03	1.26E-02	3.19E-07	1.13E-03	3.88E-02
S1.Excavation 0.4 m depth	2.38E+00	1.42E-09	2.69E-09	4.05E-07	4.06E-04	1.46E-02	7.35E-02	1.87E-06	6.60E-03	2.25E-01
S1.Excavation and blasting	1.64E+01	5.40E-09	1.90E-08	2.89E-06	2.91E-03	1.49E-01	7.93E-01	1.28E-05	7.16E-02	1.56E+00
S1.Excavation other	3.38E+00	1.99E-09	3.84E-09	5.79E-07	5.75E-04	2.07E-02	1.04E-01	2.67E-06	9.35E-03	3.21E-01
S1.External soil	1.04E+01	3.75E-09	1.58E-08	3.94E-06	1.01E-03	3.48E-02	1.53E-01	8.90E-06	1.34E-02	4.31E+00
S1.Fine- and coarse fraction separation	1.68E+00	6.15E-10	2.16E-09	3.30E-07	2.72E-04	1.00E-02	5.03E-02	1.46E-06	4.50E-03	1.78E-01
S1.Hazardous waste transportation	6.38E+00	2.30E-09	9.64E-09	2.41E-06	4.05E-04	1.06E-02	3.17E-02	5.45E-06	2.55E-03	2.64E+00
S1.Land refill	1.71E+01	6.24E-09	2.19E-08	3.35E-06	2.94E-03	1.06E-01	5.31E-01	1.48E-05	4.75E-02	1.81E+00
S1.Landfill	7.55E+00	5.83E-09	2.65E-07	2.75E-05	3.67E-03	7.98E-02	1.57E-01	5.54E-05	1.09E-02	1.01E+02
S1.Noise barrier	3.20E+00	1.17E-09	6.19E-07	4.67E-05	5.51E-04	1.98E-02	9.95E-02	2.78E-06	8.91E-03	1.08E+02
S1.Rock debris separation	1.07E+01	3.90E-09	1.37E-08	2.09E-06	2.10E-03	7.47E-02	3.82E-01	9.26E-06	3.43E-02	1.13E+00
S1.Total	**7.95E+01**	**3.27E-08**	**9.73E-07**	**9.03E-05**	**1.49E-02**	**5.22E-01**	**2.39E+00**	**1.16E-04**	**2.11E-01**	**2.21E+02**
S2.Dock	3.67E-01	1.34E-10	4.71E-10	7.19E-08	6.57E-05	2.47E-03	1.26E-02	3.19E-07	1.13E-03	3.89E-02
S2.Excavation 0.4 m depth	2.38E+00	1.42E-09	2.69E-09	4.05E-07	4.06E-04	1.46E-02	7.35E-02	1.87E-06	6.60E-03	2.25E-01
S2.Excavation and blasting	1.64E+01	5.40E-09	1.90E-08	2.89E-06	2.91E-03	1.49E-01	7.93E-01	1.28E-05	7.16E-02	1.56E+00
S2.Excavation other	3.38E+00	1.99E-09	3.84E-09	5.79E-07	5.75E-04	2.07E-02	1.04E-01	2.67E-06	9.35E-03	3.21E-01
S2.External soil	2.98E+00	1.07E-09	4.50E-09	1.13E-06	2.88E-04	9.95E-03	4.36E-02	2.54E-06	3.82E-03	1.23E+00
S2.Fine- and coarse fraction separation	1.68E+00	6.15E-10	2.16E-09	3.30E-07	2.72E-04	1.00E-02	5.03E-02	1.46E-06	4.50E-03	1.78E-01
S2.Hazardous waste transportation	1.61E-01	5.90E-11	2.07E-10	3.16E-08	2.89E-05	1.09E-03	5.52E-03	1.40E-07	4.95E-04	1.71E-02
S2.Land refill	1.71E+01	6.24E-09	2.19E-08	3.34E-06	2.94E-03	1.06E-01	5.31E-01	1.48E-05	4.75E-02	1.81E+00
S2.Noise barrier	3.20E+00	1.17E-09	8.47E-07	6.62E-05	5.51E-04	1.98E-02	9.95E-02	2.78E-06	8.91E-03	2.48E+02
S2.Rock debris separation	1.07E+01	3.90E-09	1.37E-08	2.09E-06	2.10E-03	7.47E-02	3.82E-01	9.26E-06	3.43E-02	1.13E+00
S2.Total	**5.83E+01**	**2.20E-08**	**9.16E-07**	**7.70E-05**	**1.01E-02**	**4.08E-01**	**2.10E+00**	**4.87E-05**	**1.88E-01**	**2.54E+02**
S3.Dock	3.67E-01	1.34E-10	4.71E-10	7.19E-08	6.57E-05	2.47E-03	1.26E-02	3.19E-07	1.13E-03	3.89E-02
S3.Excavation 0.4 m depth	2.38E+00	1.42E-09	2.69E-09	4.05E-07	4.06E-04	1.46E-02	7.35E-02	1.87E-06	6.60E-03	2.25E-01
S3.Excavation and blasting	1.64E+01	5.40E-09	1.90E-08	2.89E-06	2.91E-03	1.49E-01	7.93E-01	1.28E-05	7.16E-02	1.56E+00
S3.Excavation other	3.38E+00	1.99E-09	3.84E-09	5.79E-07	5.75E-04	2.07E-02	1.04E-01	2.67E-06	9.35E-03	3.21E-01
S3.External soil	4.10E+00	1.47E-09	6.19E-09	1.55E-06	3.97E-04	1.37E-02	6.00E-02	3.50E-06	5.25E-03	1.69E+00
S3.Fine- and coarse fraction separation	1.68E+00	6.15E-10	2.16E-09	3.30E-07	2.72E-04	1.00E-02	5.03E-02	1.46E-06	4.50E-03	1.78E-01
S3.Hazardous waste transportation	9.58E-01	3.44E-10	1.45E-09	3.62E-07	6.08E-05	1.59E-03	4.76E-03	8.18E-07	3.82E-04	3.96E-01
S3.Land refill	1.71E+01	6.24E-09	2.19E-08	3.34E-06	2.94E-03	1.06E-01	5.31E-01	1.48E-05	4.75E-02	1.81E+00
S3.Landfill	1.13E+00	8.75E-10	3.98E-08	4.12E-06	5.50E-04	1.20E-02	2.35E-02	8.31E-06	1.63E-03	1.52E+01
S3.Noise barrier	3.20E+00	1.17E-09	8.13E-07	6.32E-05	5.51E-04	1.98E-02	9.95E-02	2.78E-06	8.91E-03	2.27E+02

S3.Rock debris separation	1.07E+01	3.90E-09	1.37E-08	2.09E-06	2.10E-03	7.47E-02	3.82E-01	9.26E-06	3.43E-02	1.13E+00
S3.Soil washing	1.21E+00	4.09E-08	3.52E-09	2.19E-07	1.35E-03	7.21E-03	2.69E-02	8.68E-06	2.42E-03	2.08E-01
S3.Total	**6.25E+01**	**6.44E-08**	**9.28E-07**	**7.92E-05**	**1.22E-02**	**4.32E-01**	**2.16E+00**	**6.73E-05**	**1.94E-01**	**2.49E+02**

APPENDIX 5: SENSITIVITY ANALYSIS RESULTS

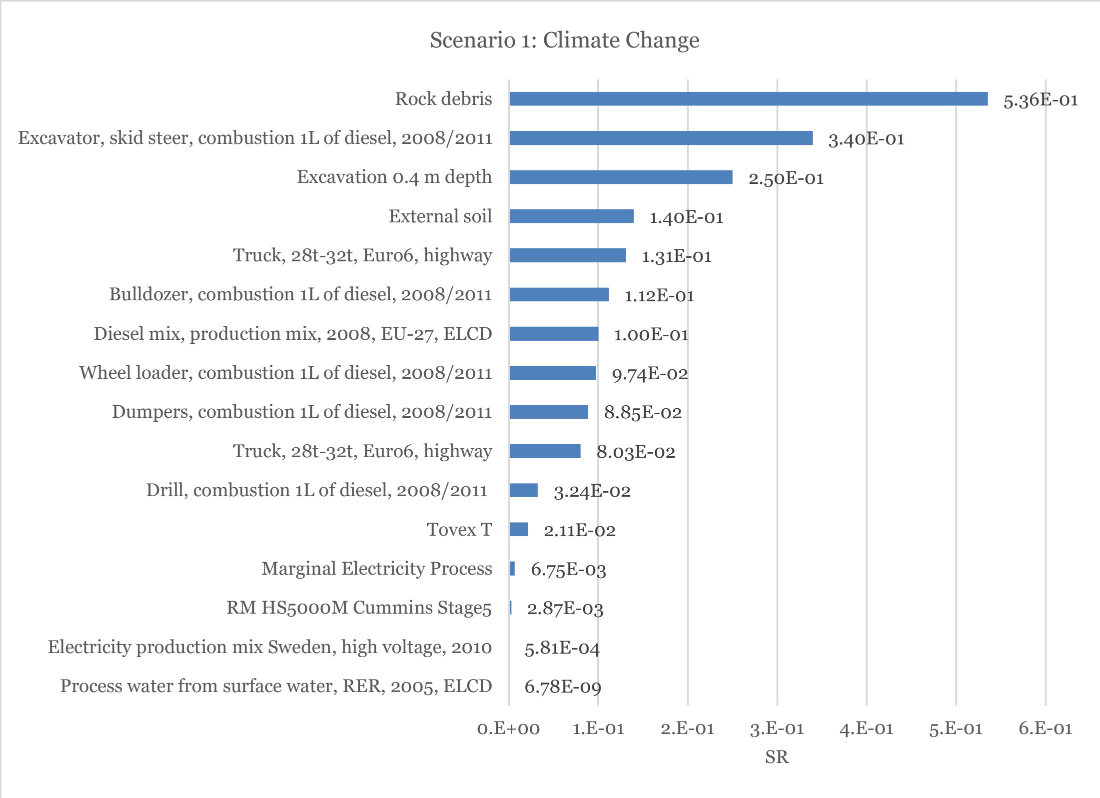

Figure 27: *Perturbation analysis results showing all parameters with a SR value above 0 for the Climate change impact category in Scenario 1.*

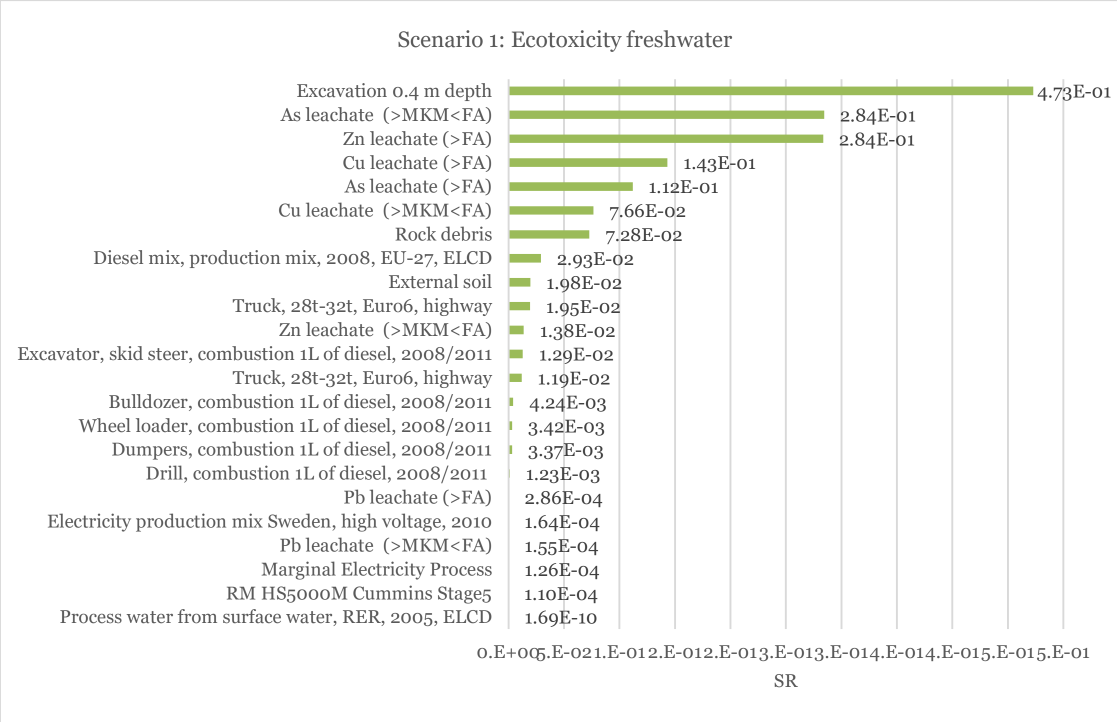

Figure 28: *Perturbation analysis results showing all parameters with a SR value above 0 for the Ecotoxicity freshwater impact category in Scenario 1.*

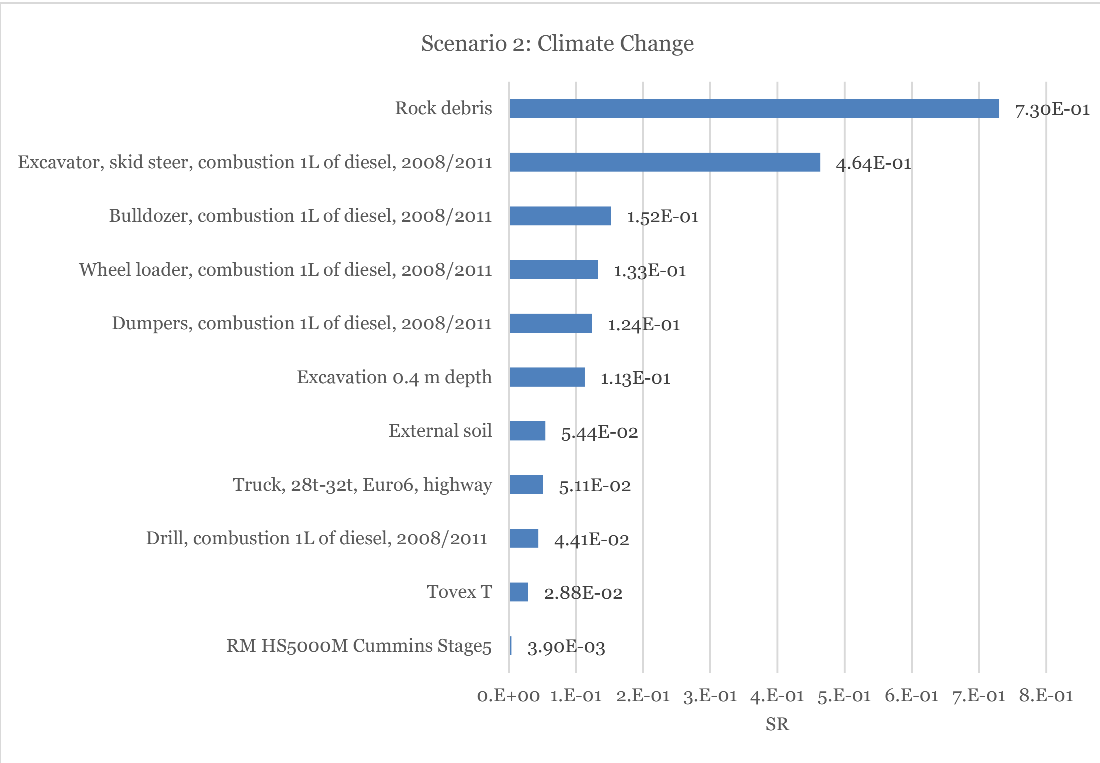

Figure 29: *Perturbation analysis results showing all parameters with a SR value above 0 for the Climate change impact category in Scenario 2.*

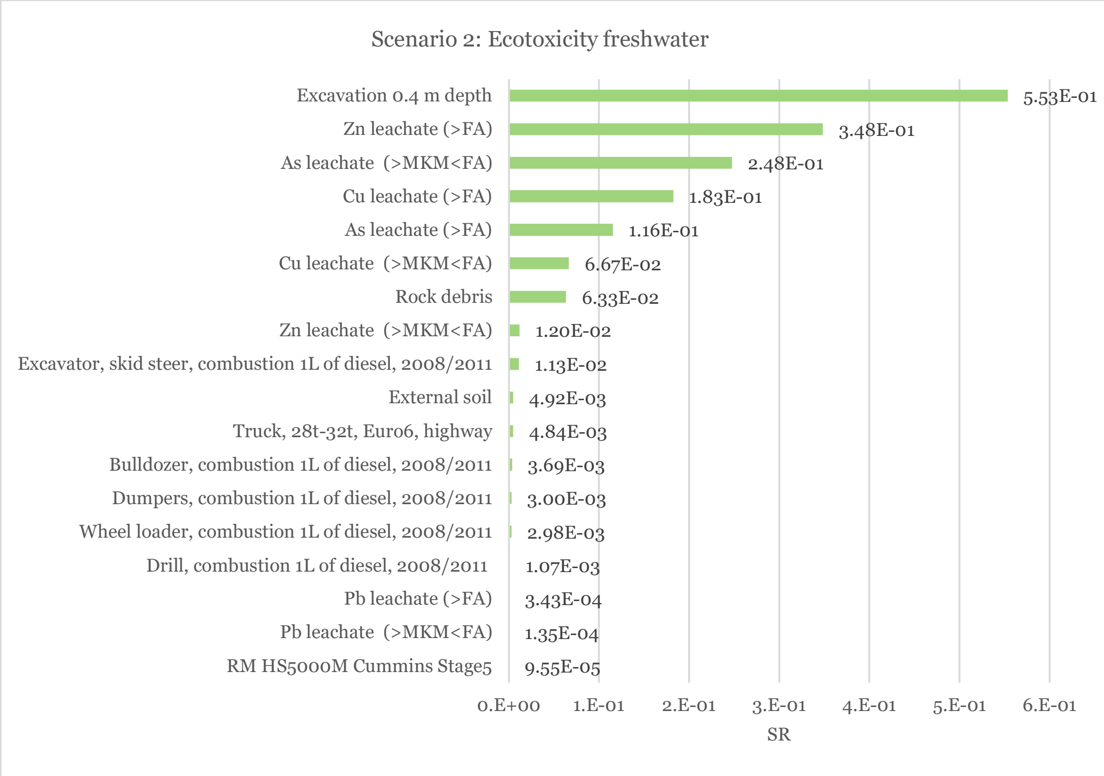

Figure 30: *Perturbation analysis results showing all parameters with a SR value above 0 for the Ecotoxicity freshwater impact category in Scenario 2.*

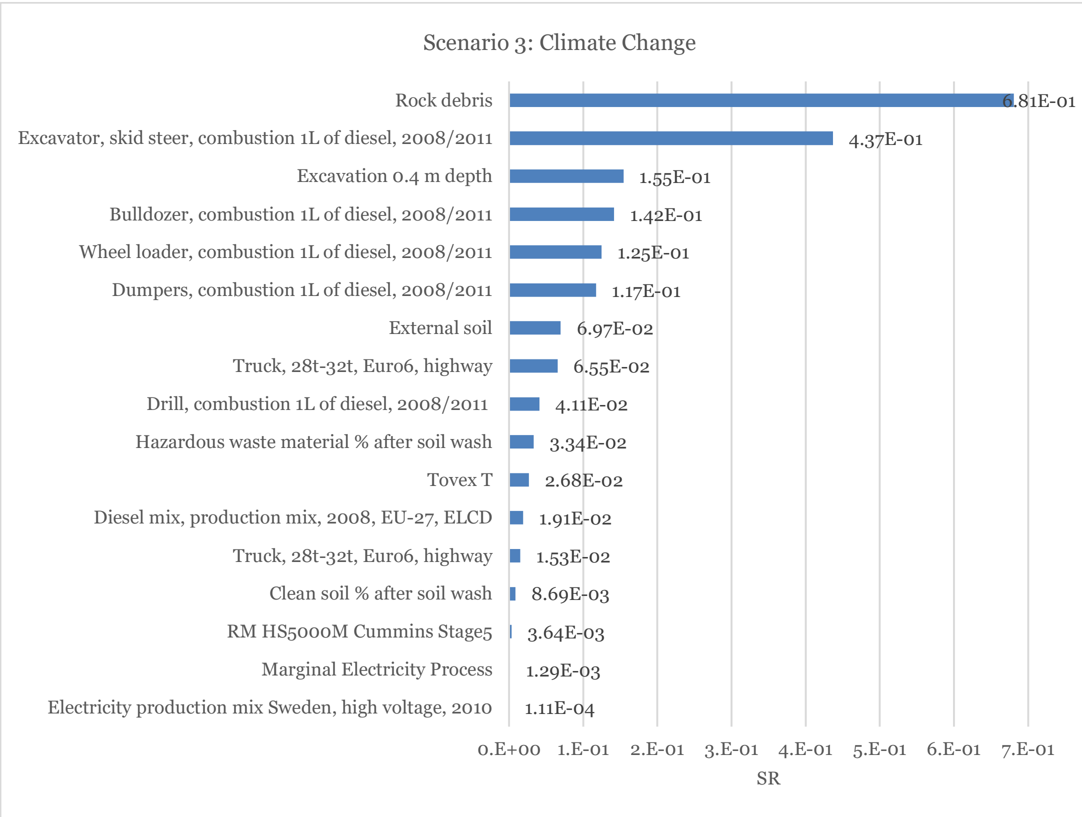

Figure 31: *Perturbation analysis results showing all parameters with a SR value above 0 for the Climate change impact category in Scenario 3.*

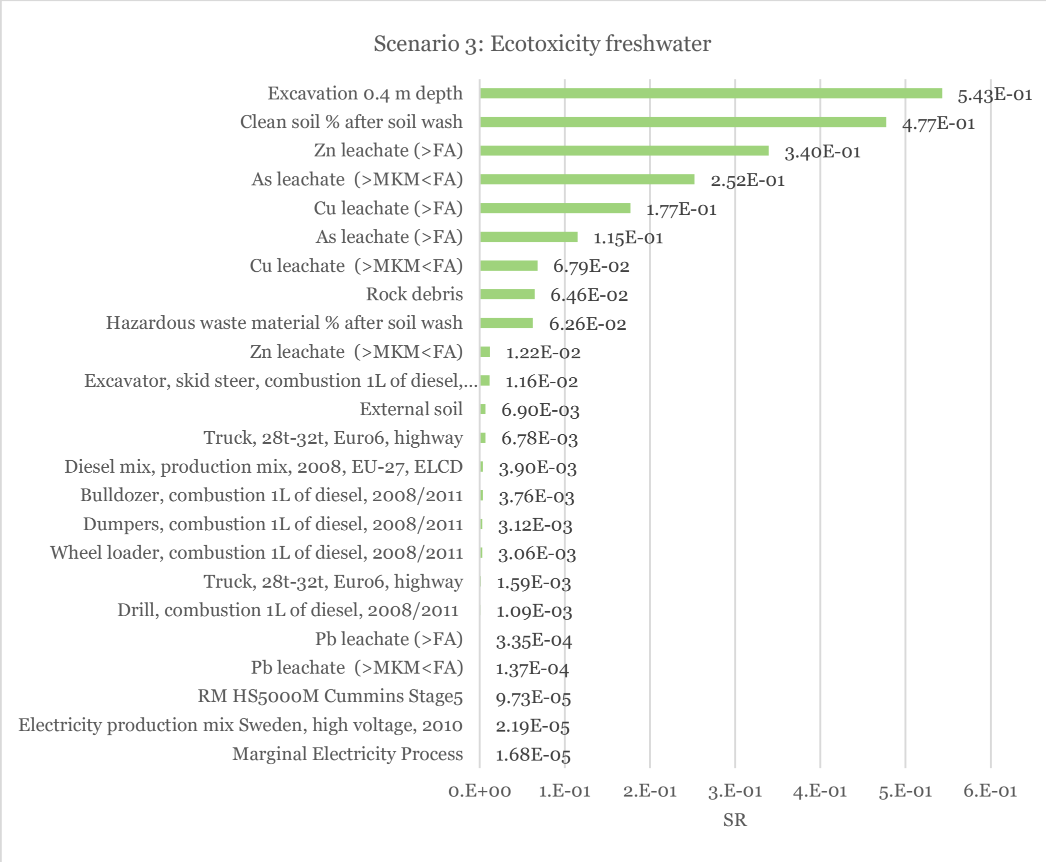

Figure 32: *Perturbation analysis results showing all parameters with a SR value above 0 for the Ecotoxicity freshwater impact category in Scenario 3.*