REPORT

SP Under Oslo

ENVIRONMENTAL IMPACT ASSESSMENTS OF URBAN GEOTECHNICAL WORKS

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Summary

One of the major contributors to global carbon emissions is the construction sector. Using world environmental input-output tables from 2009, the total CO_2-emissions from the global construction sector was calculated to account for 23% to total emissions, of which 94% were related to indirect emissions (Huang et al., 2018). Direct carbon emissions are emissions at the construction site and are related to burning of gasoline, diesel, and other petroleum products, while indirect carbon emissions are related to emissions caused by raw material extraction and manufacturing of materials. Work package 4 (WP4) of the project Under Oslo focused on quantifying the environmental impact of geotechnical works using life cycle assessment (LCA). There is currently a lack of standardization of when calculating environmental impacts from geotechnical works using LCAs, and for reporting of results from impact calculation (e.g., Kendall et al. (2018), Samuelsson et al. (2021)).

This report provides an overview of the work carried out in the work package 4 (WP4) of the project Under Oslo with the focus on "environmental impact assessments". A summary and discussion of different documents prepared in this work package is given, after which future research is suggested. The following lists some crucial findings and recommendations:

- The software SimaPro is found to be better suited than VegLCA. VegLCA is in Norway used for calculating impact from road construction but lacks the required detail to consider the specifics of geotechnical works.
- Results from the conducted LCA analyses show that the material use accounts for between 65% to 99% of the total impact depending on the environmental impact category considered. For the Life Science Building case study, the potential impact to global warming (GWP) from materials was 85%. Transport of material and machine activity accounted for a minor share of the impact, this was also true for transportation of excavated masses. Reuse of excavated masses was not accounted for in LCA of geotechnical works, as this consideration was outside the used system boundaries for the LCA for geotechnical works.
- The life cycle stages included in the LCA should follow the design and construction progress and should focus on the life stages that the professional party responsible for the process can influence. Initial calculations at early design stages can be based on approximate quantities of materials to identify processes causing so-called hot-spots with high environmental impact that should be optimized. As the design progresses, the LCA should be updated with more accurate quantities of materials and life cycle stages corresponding to transport, construction and installation process should be accounted for. As geotechnical works require little or no maintenance, and often are left in the ground, the re-use and end-of-life stages can for most scenarios be omitted.
- The system boundaries should be aligned with the NS 3451:2009 to facilitate communication with designers and contractors.

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Appendix

Review and reference page

1 Introduction

The last report from the Intergovernmental Panel on Climate Change states that global total anthropogenic greenhouse gas emissions are still increasing, with the average annual emissions being higher during 2010-2019 compared to any other decade (Pathak et al., 2022). One of the major contributors to global carbon emissions is the construction sector. Using world environmental input-output tables from 2009, the total CO_2-emissions from the global construction sector was calculated to account for 23% of the total emissions, of which 94% were related to indirect emissions (Huang et al., 2018).

Direct carbon emissions take place at the construction site and major sources are use of gasoline, diesel, other petroleum products and light fuel oil (Huang et al., 2018). Indirect carbon emissions are related to emissions caused by raw material extraction and manufacturing of used materials. Materials have also been identified as the key contributor for regional decarbonization of the building and construction sector by the UN Environment Programme (UNEP, 2022), which lists three main knowledge gaps and development areas: 1) There is currently low awareness of impact and options, 2) There is little available data and information, and 3) Materials used have high embodied carbon. One example for the latter is the cement production for the building and construction sector accounting for 8% of the global CO_2 emissions (Lehne and Preston, 2018).

As a part of the building and construction sector, geotechnical engineering design involves dimensioning of permanent and temporary underground structures. Geotechnical works are for this report defined as all works commonly planned by geotechnical engineers (Dessler and Das, 2004). Geotechnical design builds on an understanding of the local geology and hydrogeology and consider project requirements, the surrounding built environment and potential hazards, and can rely on geotechnical monitoring for ongoing verification.

For the process of constructing a building, there are numerous legal requirements and certification programs on how environmental impacts including carbon emissions should be quantified and reported. Life cycle assessments (LCAs) are widely adopted in the building and construction industry to estimate the environmental impact of buildings. Wiik et al. (2020) recently published a review of LCAs of 133 Norwegian building cases. From their work, it is, however, not clear if geotechnical works were included in the conducted LCAs.

Since 2020, the Norwegian building technical guideline (TEK-17) was updated and includes now a requirement for a LCA when establishing a new building or performing major remodelling of old buildings. Requirements for the LCA is included in TEK-17, specifying that the environmental impact should be calculated for foundations (i.e., pile foundations and shallow foundations), load bearing elements, outer walls, inner walls, floor slabs, and outer roofing (Norsk standard, 2018). However, it is not defined how geotechnical works such as, for example, ground improvement or retaining walls, should be accounted for.

According to TEK-17, the LCA should be performed as an attributional LCA, where the aim of the analysis is to attribute shares of the total impact to different parts of the system. The alternative is a consequential LCA, where the aim is to show how flows will change in response to possible decisions. The suggested functional unit (FU) for the presentation of results should be CO_2-eq. emitted over the lifetime of the building, CO_2-eq. per year, CO_2-eq. per gross floor area m^2, CO_2-eq. per gross floor area m^2 per year, or CO_2-eq. per gross floor area m^2 per user. These FUs are established and widely used in LCAs of buildings (see, for example, Wiik et al., 2022).

For geotechnical works, a unified LCA framework with defined system boundaries and FUs is still lacking (Kendall et al. 2018; Raymond et al. 2020; Samuelsson et al. 2020; Song et al. 2020). These reviews concluded that considerable discrepancies in previous LCAs of geotechnical works exist. These discrepancies are spread over the different stages of a LCA including the goal and scope definition, functional unit, system boundaries, and impact categories. A first suggestion for a framework for LCA of geotechnical works was made by Song et al. (2020). The system boundaries of an LCA describes life stages, unit processes, and inflow and outflows of the product or a system and should be relevant for the goal and the scope defined for the product or system under analysis (ISO, 2006). As outlined by Song et al. (2020), a conceptual model for geotechnical works may include site investigation, earth works, ground improvement, building foundations, and earth works in the foreground system, while fuel production, electricity, steel/rebar production, cement production, lime production, an any other relevant inputs are included in the background system. Song et al. (2020) defined the foreground system as cradle-to-site, while the background system is defined as cradle-to-gate.

Studies of LCA of geotechnical works have been published in the scientific literature. For instance, Li et al. (2010) presented endpoint impact results from analysis of an earthwork construction, where site cleaning, dewatering, excavation, pit support and backfill were included in the system boundaries. Li and Chen (2017) conducted carbon emission calculations for seven buildings where the foundation was included for one of the buildings, in addition to earth works. Song et al. (2020) performed a review of geotechnical works identifying seven papers that included geotechnical works. Five of these studies included both earthworks and foundation construction, while one included only earthworks and one only foundation construction (Li and Chen 2017, Sandanayake et al., 2016, Pujadas-Gispert et al., 2018, Luo et al., 2019, Pujadas-Gispert et al., 2020, Li and Zheng, 2020). There is currently a knowledge gap related to analysis of real-life case studies and benchmark studies that describes the environmental impact from entire geotechnical systems such as the construction and support of excavation pits.

This report summarizes work and findings related to environmental impact assessment of geotechnical works. The report is structured as follows:

- Introduction
- Identified need for research
- Summary of carried out work and results from related, prepared documents

  - Comment to TEK-17
  - Internal note 20200436-01-IN: Plaxis model
  - Conference paper: SBfin500
  - DTU-student report: Life Cycle Assessment: Excavation pit of the Life Science Building of the University of Oslo
  - Refined Life Cycle Assessment (LCA) of a Building Excavation Pit (foundation for a future publication)
  - Technical note 20200436-02-TN: Tools for assessment of sustainable environmental consequences of geotechnical works
- Discussion
- Further research needs related to environmental consequences of geotechnical works

2 Identified need for research

The following bullet points list overarching topics that require further research and that were investigated in this study:

Tools, methods and analysis:

- Available tools
- Tools suitable for geotechnical works
- Definition of system boundaries for LCA of different types of geotechnical works
- Appropriate FUs for LCA of geotechnical works
- Sources and appropriateness of inventory data
- Significance of using generic impact factors (market characterization factors) compared to product specific impact factors
- Appropriate impact categories for LCA of geotechnical works

Alignment with design process and project planning:

- Necessary level of detail of inventory data along the design process and project planning
- Timing of input of results from LCA for implementation in the design and construction process

The following section summarises documents, which were prepared in this project, and deal with these research needs.

3 Summary of results from documents prepared

3.1 Comment to TEK-17

TEK-17 is a Norwegian building Technical Regulations which describes the minimum characteristics a building must have in order to be legally constructed in Norway. The Ministry of Local Government and Modernization and the Directorate for Building Quality (DiBK) are responsible for TEK with guidance.

TEK-17 was revised in 2020 and updated with, among other things, a requirement of calculating the potential impact to climate (GWP) from materials used when new buildings are constructed, and when major remodelling of residential block and commercial buildings are done. Construction site waste should also be included in this analysis. The LCA should be done after Norwegian Standard NS 3720:2018, and include life cycle stages A1-A4, B2 and B4. The following building elements should be included (numbers in brackets referring to NS 3451:2022 system codes for buildings): Pile foundations/direct foundations (215/216), support structures (22), outer (23) and inner wall (24), floor slabs (25) and outer roofing (26).

Before TEK-17 was revised, a government consultation was published describing the planned revision, requesting comments on the content of the revision. NGI prepared a comment (see Appendix 1) recommending that the environmental impact of geotechnical works should be included when performing an LCA for new buildings.

One of the comments to the lack of requirements for GWP calculation for geotechnical work was that there is currently a lack of reference values for the total impact of geotechnical work, and for main processes of geotechnical work. If geotechnical works are going to be included in carbon footprint calculations of new buildings, this would produce reference values for the total impact, and impact from main processes. Subsequently, this results in data on the expected size of the impact from groundwork. These data can later be used to find benchmarks and maximum limits for environmental impact from geotechnical works. For a transition to a greener building and construction sector it is necessary to quantify the environmental impact from geotechnical works, and also be able to measure if the impact is high or low with the ground conditions at the site and size of the construction area.

3.2 Technical note 20200436-IN-01: Plaxis model

Six cases for different design solutions of an excavation pit were modelled using the computational modelling software Plaxis. The technical note describes the used assumptions, the conducted modelling, and the obtained results, which were subsequently used as an inventory for LCA analysis (see conference paper SBEfin500(. The technical note can be found in Appendix 2.

3.3 Conference paper: SBEfin2022

This work was presented at the SBEfin2022 conference in October 2022. The conference paper is attached in Appendix 3.

The paper describes LCA calculations and results from the four of the six design solutions for an excavation pit calculated in the 20200436-IN-01 described above. The analysis was done using the VegLCA early phase tool.

Main findings:
Hot-spot analysis

- Environmental impact was calculated as global warming potential (GWP; CO_2-eq) and acidification potential (AP; SO_4^{2-}eq.)
- GWP calculated for the excavation of masses amounted to a small share of the total GWP calculated
- Product stage accounted for the largest contribution to GWP
- Shifting the focus from minimising cost to minimising environmental impact will likely lead to different design decisions for geotechnical works

Impact categories

- Impact to the two impact categories (GWP and AP) did not increase equally as the excavation depth increased
- Results show that only accounting for GWP might lead to a false judgement with regards to the environmental performance of a design solution.
- Simple LCA calculations can provide direct comparison of the environmental impact of different geotechnical solutions

Inclusion of LCA in design process

- The level of detail of an LCA needs to be inherently connected to the level of detail of the design as the design and construction move along and information about environmental impacts needs to be available at the right point in time and at the right level of detail to adequately inform design decisions.

3.4 DTU-student report: Life Cycle Assessment: Excavation pit of the Life Science Building of the University of Oslo

This LCA was done by a group of master students at The Danish Technical University (DTU), supervised by NGI. The life cycle inventory (LCI) for the Life Science Building (LSB) was constructed during the work of the students, however, there were large uncertainties in the quantities for materials, especially for steel in the steel core piles. The report prepared by the students can be found in Appendix 4.

Summary and main findings:

Hot-spot analysis

- LCA performed for the main processes: excavation of masses, soil stabilization, sheet pile wall, steel core piles, anchoring of sheet pile wall and ground floor slab
- In each main process, transport of machines and materials were included, as well as the machine activity
- The largest environmental impact was obtained for the steel core piles (i.e., hotspot).

Impact categories

- Environmental impact was calculated for 18 environmental impact categories available in SimaPro. The different processes show different impact to the different impact categories. The steel core piles had the largest environmental impact to 14 impact categories while the excavation of masses (largest environmental impact to one impact category), soil stabilization (largest environmental impact to two impact categories) and the sheet pile wall (largest environmental impact to one impact category) had a minor impact.

3.5 Refined Life Cycle Assessment (LCA) of a Building Excavation Pit

As there were uncertainties and inaccuracies in the data used for the LCI for the student report, the LCI of the LSB was updated with data from as-built drawings after completion of the geotechnical works for the excavation pit. A refined LCA was then performed for the main processes: excavation, transport of excavated masses, soil stabilization, sheet pile wall, pipe pile wall, anchors and walers, piles. For all main processes, transport of machinery and materials was also included, in addition to machine activity needed for establishment of the different structures. This work will provide the foundation for a future publication.

- The respective analysis was performed using SimaPro, with ReCiPe 2016 midpoint using the Hierarchist version.

Main findings:

Hot-spot analysis

- Materials account for the largest impact to all categories, between 65 and 99%
- Impact to GWP from materials was 85%

- Across all impact categories except for ionizing radiation, the piles had the largest impact. For ionizing radiation, the impact from the soil stabilization was slightly larger.
- Geotechnical design should focus on minimizing quantities of materials, and identifying low-carbon/low-resource intensive material alternatives

Impact categories

- Environmental impact was calculated for the 18 impact categories available in SimaPro
- The impact from main processes varies between the different categories, strengthening the recommendation of calculating the impact to additional categories beyond GWP

LCA framework for geotechnical works

- To standardize LCA for geotechnical works there is a need for further work with defining system boundaries and agreeing on a functional unit
- From the LCA of the LSB the system boundaries include: excavation, transport of excavated masses, soil stabilization, sheet pile wall, pipe pile wall, anchors and walers and piles. For all main processes, transport of machinery and materials was also included, in addition to machine activity needed for establishment of the different structures. This corresponds to life stages A1, A2, A3, A4 and A5, or a cradle-to-site analysis which was found to be an adequate system boundary for geotechnical works as long as most of the structures are left in the ground after the building is established. However, in the future, it is expected that a higher share of the materials will be extracted from the ground after the building is established and recycled or reused. Thus, end of life stages (C1, C2, C3 and C4) and processes beyond the building life cycle stages (D) could be included.
- The main processes identified in the LCA of the LSB: excavation, transport of excavated masses, soil stabilization, sheet pile wall, pipe pile wall, anchors and walers, and piles are suggested to describe the main processes of geotechnical works for an excavation pit for a building. In addition, the inclusion of ground water control should be considered in the future.

Inclusion of LCA in the design process

- LCA of geotechnical works was suggested to be performed in parallel with the design and execution process to access inventory data with highest possible level of detail and characterization factors describing the environmental impact at an appropriate level.

3.6 Technical note 02 (TN-02): Tools for assessment of sustainable environmental consequences of geotechnical works

With the LCI of the LSB, an additional analysis of the environmental impact from establishing an excavation pit was calculated using VegLCA. The aim was to compare the "tidlig-fase"-tool of VegLCA with SimaPro. Appendix 5 shows this technical note.

Summary and main findings:

- Analysis performed using both VegLCA and SimaPro
- The processes in "tidlig-fase" VegLCA do not match very well with the materials used at LSB. SimaPro allows for full flexibility when selecting processes to represent materials used, however, the processes represent market values which are average values for several products.
- VegLCA provides an easy initial calculation of environmental impact, while SimaPro is more complex
- More environmental impact categories are calculated using SimaPro, only CO_2-eq. available in VegLCA
- The total GWP calculated using the two tools are similar. Hence, the VegLCA early-phase tool may be adopted for first pass assessments at early project stages.

4 Discussion

As the comment to the TEK-17 revision showed, geotechnical works are often neglected in the calculation of environmental impacts when new buildings are constructed. The requirement for calculating the carbon footprint currently only applies to materials in the new building, including pile foundations. The work summarised in this report aimed to overcome the shortcoming of neglecting geotechnical works in environmental impact assessments of building construction. In addition, this study focused on identifying suitable software tools for calculating environmental impact from geotechnical works, clarifying details in the method for calculating the environmental impact (e.g., system boundaries, functional units and environmental impact categories), and producing reference values for geotechnical works and from single main processes of geotechnical work.

4.1 Available tools and suitability for assessment of geotechnical works

Two existing software tools have been used: VegLCA, a excel-based tool for calculating the impact from road-construction and SimaPro, a software developed for LCAs of many different types of products and services. SimaPro has several databases with impact factors that can be used to calculate and describe the total environmental impact from processes. Several methods for impact calculation are also available.

VegLCA

- VegLCA is developed in excel and has two modules: Early-phase and late-phase. Early phase should be used when the project is in its early phases and the quantities and qualities of materials are not well known, while the late phase tool should be used when these are known in detail. The tool has standard calculation factors and emission factors included. These can be replaced by project specific factors. The late phase tool is built after the process codes from *Vegvesenets Prosseskode 1 og 2 (2015)*.
- VegLCA can be downloaded free of charge, together with a user manual and documentation.
- VegLCA presents tons CO2e from early phase.

SimaPro

- SimaPro is a licensed software developed for analysis of complex life cycles. The tool has libraries with many different processes that can be included in the analysis, and also allows for building custom processes to include in the analysis. SimaPro has several different libraries with impact factors for the processes included in the tool. Several methods are available for calculating impact.
- SimaPro calculates impact to eighteen impact categories.

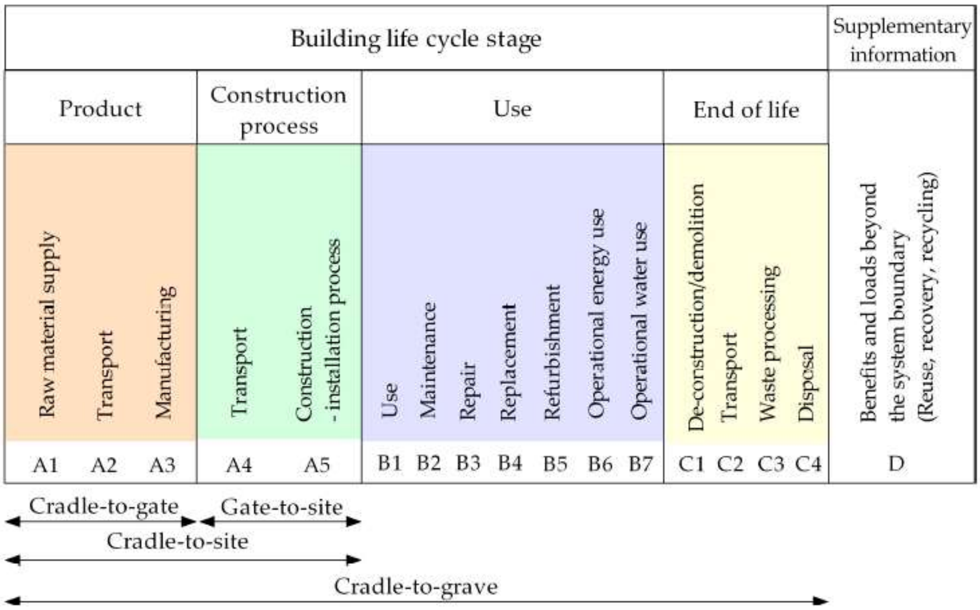
Results using the early phase tool in VegLCA and SimaPro with the same input data showed that the quantity of CO2-eq calculated with the two tools was similar (see Sections 3.5 and 3.6). There were challenges to using VegLCA for calculating the impact from the geotechnical works at LSB. In VegLCA, it was difficult to find processes that could represent the materials at LSB accurately. For instance, the Multicem 50/50 is represented by Normalbetong, B35, bransjereferanse. Multicem 50/50 was not available in the early phase tool. The late phase tool has a section called *Constructions in the ground*, which mainly describes transport and machinery activities and do not account for the impact from the production of the materials.

The steel piles caused the largest contribution to GWP with both tools, however, the share was significantly different between the two tools. VegLCA reported 50% of GWP caused by steel core piles, while SimaPro reported 36%. The GWP from the transport of excavated masses was equal between the two tools (i.e., 9%). Also, the machine activity was rather similar: 8% in VegLCA and 6% in SimaPro.

The work described above show that it is possible to use VegLCA to get an overview over the impact from the different process, however, the results should be considered with caution. It is recommended to rather use the model developed as a part of the case study of assessment of impact from the geotechnical works at LSB which is available in SimaPro. Even though the impact calculated in SimaPro are based on generic market emission factors, this tool is more suited to provide a first overview of hot-spots and processes that should be targeted for optimization to reduce the environmental impact.

4.2 System boundaries

System boundaries define which processes should be included in the LCA, and what life stages should be included. Building life cycle stages are shown in Figure 1. Lee and Basu (2022) included a figure describing the system boundaries of drilled shafts in sand which can be an illustration of generic system boundaries of geotechnical works, see Figure 2.



Building life cycle stage																Supplementary information
Product			Construction process		Use							End of life				
Raw material supply	Transport	Manufacturing	Transport	Construction - installation process	Use	Maintenance	Repair	Replacement	Refurbishment	Operational energy use	Operational water use	De-construction/demolition	Transport	Waste processing	Disposal	Benefits and loads beyond the system boundary (Reuse, recovery, recycling)
A1	A2	A3	A4	A5	B1	B2	B3	B4	B5	B6	B7	C1	C2	C3	C4	D

Figure 1 Building system boundaries for LCA analysis (from Song et al., 2020).

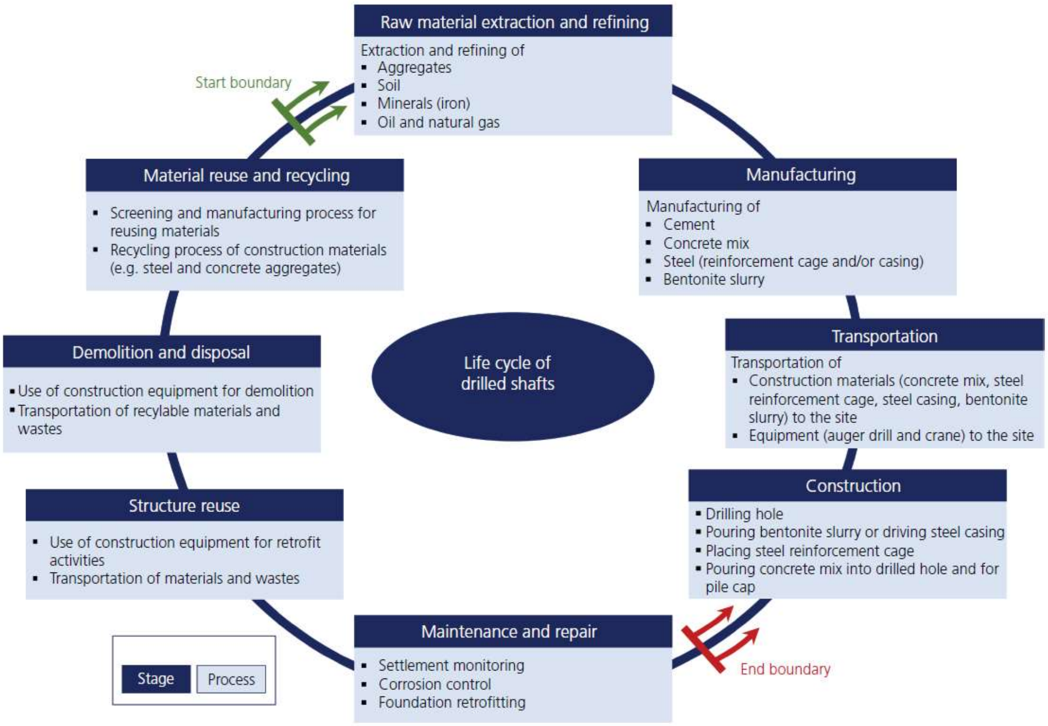


Figure 2 Life cycle of drilled shafts in sand (from Lee and Basu, 2022).

From the LSB case study, it is recommended that a detailed LCA of geotechnical works is performed as cradle-to-site analyses, including phases A1, A2, A3, A4 and A5. Geotechnical structures are for now generally left in the ground, and no use-phase is relevant to include, neither end-of-life.

The processes that should be included in an LCA for geotechnical works should be aligned with the NS 3451:2009 to facilitate for communication with the design process and contract organization:

- Site preparation
- Excavation pit
- Soil stabilization
- Support structures,
  - Earth retaining structures
  - Anchoring and walers
- Piles foundations
- Direct foundations
- Drainage
- Equipment and completion
  - Transportation of excavated masses
- Other geotechnical work

- Ground water control

The system boundaries for the framework developed during Under Oslo for the assessment of the case study LSB is shown in Figure 3. Table 1 shows the different processes included and the representative processes in SimaPro.

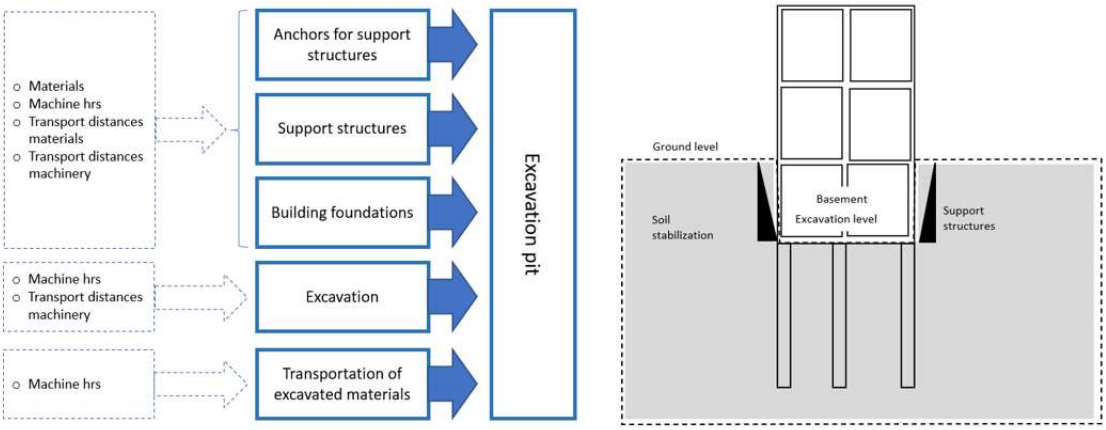


Figure 3 System boundaries for LCA of an excavation pit developed during the work with the case study Life Science Building.

Table 1 SimaPro model and processes used for calculating the environmental impact of geotechnical works.

Process	Input data	Simapro
LCC	Multicem 50/50	Cement, blast furnace slag 36-65% {Europe without Switzerland}| cement production, blast furnace slag 36-65% | Cut-off, U
	Machine hours	Machine operation, diesel, >=74.57 kW, high load factor {GLO}| machine operation, diesel, >=74.57 kW, high load factor | Cut-off, U
	Transport materials	Transport, freight, lorry >32 metric ton, euro6 {RER}|market for transport, freight, lorry >32 metric ton, EURO6 | Cut-off, U
	Transport machinery	Transport, freight, lorry >32 metric ton, euro6 {RER}|market for transport, freight, lorry >32 metric ton, EURO6 | Cut-off, U
SPW	SPW	Steel, low-alloyed, hot rolled {GLO}| market for | Cut-off, U
	Dowel and casing	Steel, low-alloyed, hot rolled {GLO}| market for | Cut-off, U
	Machine hours	Machine operation, diesel, >=74.57 kW, high load factor {GLO}| machine operation, diesel, >=74.57 kW, high load factor | Cut-off, U
	Transport materials	Transport, freight, lorry >32 metric ton, euro6 {RER}|market for transport, freight, lorry >32 metric ton, EURO6 | Cut-off, U
	Transport machinery	Transport, freight, lorry >32 metric ton, euro6 {RER}|market for transport, freight, lorry >32 metric ton, EURO6 | Cut-off, U
PPW	PPW	Steel, low-alloyed, hot rolled {GLO}| market for | Cut-off, U
	Machine hours – drill rig	Machine operation, diesel, >=74.57 kW, high load factor {GLO}| machine operation, diesel, >=74.57 kW, high load factor | Cut-off, U
	Machine hours – excavator	Machine operation, diesel, >=18.64 kW and <74.57 kW, high load factor {GLO}| machine operation, diesel, >=18.64 kW and <74.57 kW, high load factor | Cut-off, U
	Machine hours - compressor	Machine operation, diesel, <18.64 kW, high load factor {GLO}| machine operation, diesel, <18.64 kW, high load factor | Cut-off, U
	Transport materials	Transport, freight, lorry >32 metric ton, euro6 {RER}|market for transport, freight, lorry >32 metric ton, EURO6 | Cut-off, U
	Transport machinery	Transport, freight, lorry >32 metric ton, euro6 {RER}|market for transport, freight, lorry >32 metric ton, EURO6 | Cut-off, U
Anchors and walers	Temporary wire anchor	Steel, low-alloyed, hot rolled {GLO}| market for | Cut-off, U
	Permanent wire anchor	Steel, low-alloyed, hot rolled {GLO}| market for | Cut-off, U
	Tendon	Steel, low-alloyed, hot rolled {GLO}| market for | Cut-off, U
	Casings	Steel, low-alloyed, hot rolled {GLO}| market for | Cut-off, U
	Anchors and anchor head	Steel, low-alloyed, hot rolled {GLO}| market for | Cut-off, U
	Injection grout	Cement, Portland {Europe w
	Walers	Steel, low-alloyed, hot rolled {GLO}| market for | Cut-off, U
	Machine hours – drill rig	Machine operation, diesel, >=74.57 kW, high load factor {GLO}| machine operation, diesel, >=74.57 kW, high load factor | Cut-off, U
	Machine hours – excavator	Machine operation, diesel, >=18.64 kW and <74.57 kW, high load factor {GLO}| machine operation, diesel, >=18.64 kW and <74.57 kW, high load factor | Cut-off, U
	Machine hours – compressor	Machine operation, diesel, <18.64 kW, high load factor {GLO}| machine operation, diesel, <18.64 kW, high load factor | Cut-off, U
	Transport materials	Transport, freight, lorry >32 metric ton, euro6 {RER}|market for transport, freight, lorry >32 metric ton, EURO6 | Cut-off, U
	Transport machinery	Transport, freight, lorry >32 metric ton, euro6 {RER}|market for transport, freight, lorry >32 metric ton, EURO6 | Cut-off, U
Building foundations	Steel core piles	Steel, low-alloyed, hot rolled {GLO}| market for | Cut-off, U
	Casings	Steel, low-alloyed, hot rolled {GLO}| market for | Cut-off, U
	Injection grout	
	Machine hours – drill rig	Machine operation, diesel, >=74.57 kW, high load factor {GLO}| machine operation, diesel, >=74.57 kW, high load factor | Cut-off, U
	Machine hours – excavator	Machine operation, diesel, >=18.64 kW and <74.57 kW, high load factor {GLO}| machine operation, diesel, >=18.64 kW and <74.57 kW, high load factor | Cut-off, U
	Machine hours – compressor	Machine operation, diesel, <18.64 kW, high load factor {GLO}| machine operation, diesel, <18.64 kW, high load factor | Cut-off, U
	Transport materials	Transport, freight, lorry >32 metric ton, euro6 {RER}|market for transport, freight, lorry >32 metric ton, EURO6 | Cut-off, U
	Transport machinery	Transport, freight, lorry >32 metric ton, euro6 {RER}|market for transport, freight, lorry >32 metric ton, EURO6 | Cut-off, U
Excavation	Excavation of masses	Excavation, hydraulic digger {RER} | processing | Cut-off, U
	Transport machinery	Transport, freight, lorry >32 metric ton, euro6 {RER}|market for transport, freight, lorry >32 metric ton, EURO6 | Cut-off, U
Transportation of excavated masses	Contaminated masses	Transport, freight, lorry >32 metric ton, euro6 {RER}|market for transport, freight, lorry >32 metric ton, EURO6 | Cut-off, U
	Non-contaminated masses – land transport	Transport, freight, lorry >32 metric ton, euro6 {RER}|market for transport, freight, lorry >32 metric ton, EURO6 | Cut-off, U
	Non-contaminated masses –sea transport	Transport, freight, sea, container ship {GLO}| market for transport, freight, sea, container shop | Cut-off, U
	Ordinary and inert waste	Transport, freight, lorry >32 metric ton, euro6 {RER}|market for transport, freight, lorry >32 metric ton, EURO6 | Cut-off, U
	Non-contaminated masses with waste	Transport, freight, lorry >32 metric ton, euro6 {RER}|market for transport, freight, lorry >32 metric ton, EURO6 | Cut-off, U

4.3 Appropriateness and source of inventory data

The LCA and level of detail of input data should follow the design process because input data with a higher level of detail and accuracy can be expected as a project progresses. For initial calculations, the focus should be on identifying environmental hot-spots during the design processes, and for most cases it is likely sufficient to include phases A1, A2 and A3. Approximate data on transport and machinery activity can be included. However, as the analysis of LSB showed, these cause minor impact and thus should not be the main concern. The geotechnical design also generally does not have a main influence on transport distances.

In the design phase, geotechnical engineers can influence: 1) The type of solution selected, 2) The quantity of materials, 3) Provide recommendations on quality of materials. Thus, results from LCA should function as a decision support to select the geotechnical solution and quantity of material that has the lowest possible impact to the environment without compromising on the safety requirements of the structure. During execution, contractors, and to some degree site owners, can control and influence transport and installation processes. Results from LCA during execution should therefore to a greater degree focus on minimising transport distances and thus where the material suppliers are located.

The level of accuracy of the inventory data increases as the design and execution phase progress. This is tentatively illustrated in Figure 4, where the design phase is suggested to start with an LCA where approximate quantities of materials from rough calculations and generic emissions factors are used. The results can be used for identifying processes with high impact. Further, as the level of detail of quantities increases the LCA should be updated. Integrating emission factors in Building Information Modelling (BIM), which considers geotechnical works, would facilitate for easy calculation of impact from material quantities as the design of the geotechnical work progress.

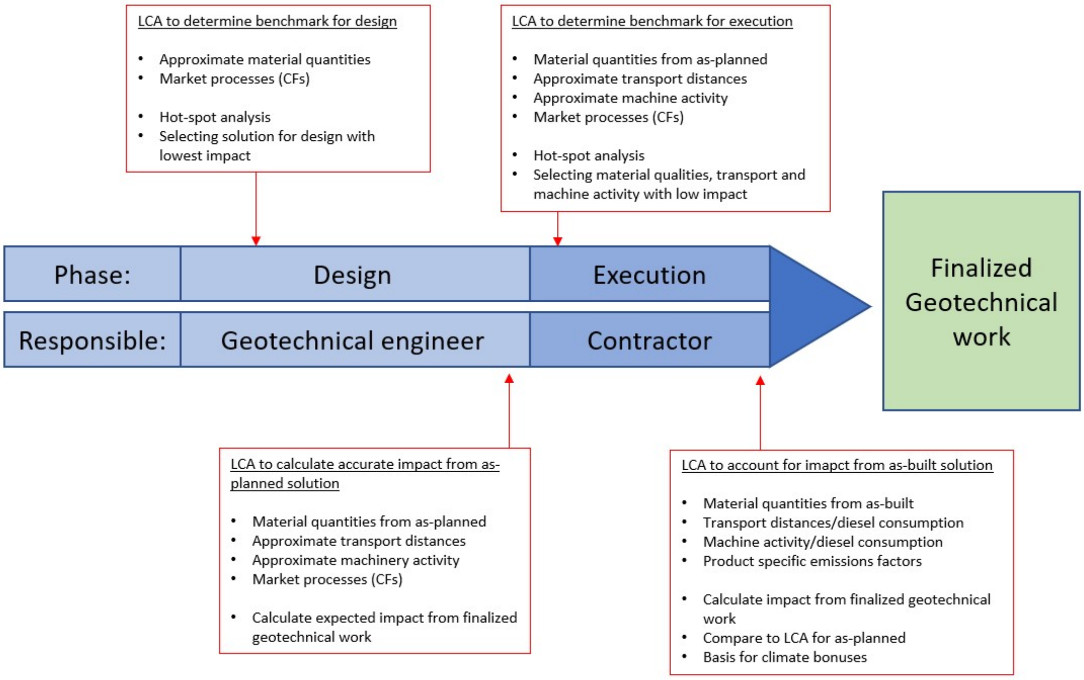


Figure 4 Progress from geotechnical design to execution to finalized geotechnical work, with suggested timing to perform LCA to work as decision foundation.

A detailed LCA can be delivered together with the detailed design of the solution. This can, for example, be used as a basis for calculating climate bonuses for contractors.

The level of accuracy of an LCA and the usefulness of the results rely to a large degree on the input data. Obtaining accurate quantities of the used materials as inventory data was a huge challenge for the LCA of the LSB. The final analysis was mainly based on as-built data. Using as-built data results in a high accuracy of the results. However, when using as-built data, the LCA is produced to report on the results after the work is finalized and not to support decisions during the project. After the work with the LSB, it seems more important to align the analysis with the design process to facilitate for inclusion of results in decision-making, rather than a obtaining a high level of accuracy of the input data. LCA results get full value when they are included in the decision-making processes.

4.4 Functional unit

Functional units are used to calculate reference values for comparison between analysis or between alternatives for the same design. For buildings, an established functional unit used for calculating reference values is "1 m^2 of floor space over the lifetime of the building". For geotechnical work, it is harder to find one generic FU, as geotechnical work is performed for a wide variety of construction processes (e.g., road, railway, buildings).

For geotechnical works for buildings, the FU should be aligned with the FU used for assessing the environmental impact of a building. In addition, the quantification of floor space should be standardized. From the work with the LSB, gross floor area is suggested as a standardized measure of floor space.

For geotechnical works for other structures than buildings, a preliminary suggestion is to present the total impact and then present detailed, quantitative specifications on depth of the excavation pit, circumference of excavation pit, length of sheet pile wall, depth of sheet pile wall, number of foundation piles etc. This can facilitate for calculation of different reference values. Also, the impact for main processes can be presented as impact per pile, impact per m of sheet pile wall. For excavation pits of linear infrastructure projects (e.g., rail and road), a generic FU of "1 m^3 over the lifetime of the structure" has been suggested.

4.5 Impact categories

Impact categories describe different environmental impacts from the product or services that are being analysed. To calculate the total environmental impact, the impact per unit of a process needs to be described by a characterization factor. For emissions of carbon dioxide and other climate gasses this is also called emission factor. This is for instance kg of CO_2 emitted per kg steel produced. However, as not all environmental impacts are emissions, these factors are called characterization factors, or CFs for short.

The libraries in SimaPro contain CFs for eighteen environmental impact categories. These are shown in Table 2 below. The work with LSB showed that the different processes have different impact to different categories. Based on this work, it is recommended to calculate more impact categories than GWP. This is to avoid shifting the environmental impact to other categories when reducing the impact to for instance GWP. Discussion of results can focus on a selected number of impact categories, for instance, a selection can be based on the planetary boundaries presented by Steffen et al. (2015). This should be evaluated for the specific analysis, as this is also dependent on the service or product analysed.

Table 2 Impact categories from SimaPro.

Impact category	Abb.	Unit
Global warming	GWP	kg CO2 eq
Stratospheric ozone depletion	ODP	kg CFC11 eq
Ionizing radiation	IRP	kBq Co-60 eq
Ozone formation, Human health	EOFP	kg NOx eq
Fine particulate matter formation	PMFP	kg PM2.5 eq
Ozone formation, Terrestrial ecosystems	HOFP	kg NOx eq
Terrestrial acidification	TAP	kg SO2 eq
Freshwater eutrophication	FEP	kg P eq
Marine eutrophication	MEP	kg N eq
Terrestrial ecotoxicity	TETP	kg 1,4-DCB
Freshwater ecotoxicity	FETP	kg 1,4-DCB
Marine ecotoxicity	METP	kg 1,4-DCB
Human carcinogenic toxicity	HTPc	kg 1,4-DCB
Human non-carcinogenic toxicity	HTPnc	kg 1,4-DCB
Land use	LOP	m2a crop eq
Mineral resource scarcity	SOP	kg Cu eq
Fossil resource scarcity	FFP	kg oil eq
Water consumption	WCP	m3

5 Further research needs related to sustainable environmental consequences of geotechnical works

During the work with sustainable environmental consequences of geotechnical works a framework for LCA of geotechnical works was established, with a recommendation on system boundaries, FU, impact categories and source of inventory data.

The following are a prioritized list of further research and development needs:

- Produce benchmark data for different processes of geotechnical works in different ground conditions, for instance kg CO_2eq per m sheet pile wall
- Apply the established framework to perform LCAs for additional excavation pits which together with values from LSB can be used to establish reference values (i.e., benchmark data of environmental impacts of geotechnical works)
- Implement generic characterization/emission factors for calculation of GWP in BIM models to facilitate for easy initial calculation of sustainable environmental consequences of geotechnical works
- Compare as-built with as-planned calculations to identify significant differences in order to better evaluate the reliability of LCAs at initial project phases
- Compare market CFs with specific CFs to see how sensitive the obtained results are with respect to the input data

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Appendix 1

HØRINGSSVAR TIL KLIMABASERTE ENERGIKRAV TIL BYGG („COMMENT TO TEK 17”)

Stiftelsen Norges Geotekniske Institutt (NGI)

30.09.2021

Høringssvar til Klimabaserte energikrav til bygg

Til DiBK.

Vedlagt er høringsuttalelse fra NGI.

Se vedlegg

- Høringssvar fra NGI_2021-09-30.pdf

Direktoratet for byggkvalitet
v/Christine Molland Karlsen
Postboksd 8742 Youngstorget
0028 Oslo

DATO
2021-09-30

VÅR REF
Høringssvar til DiBK

DERES REF
Klimabaserte energikrav til bygg

Kommentar til høring: Klimabaserte energikrav til bygg

IPCC sin siste rapport erklærte at det var kode rød for planeten og krever kraftig tiltak for å redusere utslipp av klimagasser og overforbruket av ressurser. Bygg, anlegg- og eiendomssektoren (BAE-sektoren) står globalt for om lag 40 % av klimagassutslippene. I Norge er BAE-sektoren pekt ut som en av bransjene der det er størst potensial for reduksjon i utslipp av klimagasser og forbruk av ressurser. NGI gir råd til aktører innenfor bygg og anlegg som lenge har anerkjent sitt bidrag til reduksjon av utslipp av klimagasser og forbruk av ressurser, og som derfor har utarbeidet tydelige og ambisiøse klima- og miljømål. ***For at vi skal få virkelig fart på teknologiutviklingen og satsningen mot et grønt skifte innenfor bygg og anlegg må det utformes lover, regelverk og forskrifter som står de til ambisiøse miljømålene vi alle ønsker å jobbe mot.*** Slik utkastet til ny tekst i TEK-17 står nå er ikke denne i nærheten av å reflektere kunnskapen og viljen til innovasjon i sektoren. Regelverket må være med på å sette tydelige, klare og ambisiøse miljømål som står i forhold til miljømålene som Norge har satt seg. I denne sammenhengen er grunnarbeider og fundamenter ressurs- og klimagassintensive prosesser som bør og skal tas med i kvantifiseringen av klima og miljøpåvirkning for bygninger. ***NGI mener at det er svært uheldig at grunnarbeid, fundamenter og transport av materialer og løsmasser ikke inkluderes når beregninger av klima og miljøpåvirkninger fra bygninger tas inn i ny tekst til TEK17.*** Nedenfor har vi beskrevet hvorfor vi mener at krav til kvantifisering av klima og miljøpåvirkning fra grunnarbeider og fundamenter bør tas inn.

Det finnes allerede bred og inngående kunnskap om hvordan klima og miljøpåvirkning fra grunnarbeider og fundamenter kan reduseres, og det finnes metodikk for å kvantifisere denne påvirkningen. NGI har, alene og sammen med våre samarbeidspartnere, mange forsknings- og rådgivningsprosjekt der vi ser på hvordan vi kan kvantifisere og redusere klima og miljøpåvirkningen fra grunnarbeider og fundamenter. Sammen med Regionalt Forskningsfond Trøndelag har vi i prosjektet SUSI (*Sustainable soil improvement*) funnet ut at mengden kalk og sement i kalk-sement-peler kan tilpasses lokale forhold og reduseres med opptil 50 % sammenlignet med det som ville vært standard mengde bindemiddel uten lokal tilpasning. Dette gir tilsvarende reduksjon i mengden klimagassutslipp fra kalk og sementproduksjon. Mer info om prosjektet og beregningene av klima og miljøpåvirkning ligger her: https://www.ngi.no/eng/Projects/SUSI-Sustainable-Soil-Improvement. Statsbygg, Bane NOR og Statens vegvesen har med støtte fra Innovasjon Norge et prosjekt som Multiconsult leder sammen med en rekke partnere fra industrien som omhandler reduksjon av klimagassutslipp fra grunnstabilisering. Prosjektet heter Klimagrunn, les mer her: https://www.tu.no/artikler/nar-disse-forskerne-har-lost-kalksementgaten-kan-utslippene-fra-bygg-og-anlegg-ga-drastisk-ned-br/512855. Prosjektet GOAL har som hovedmålet å gjøre jordstabilisering mer bærekraftig og digitalisert gjennom å benytte nyeste former for sensorteknologi og datahøsting, samt restprodukter fra industrien: https://kommunikasjon.ntb.no/pressemelding/15-millioner-til-baerekraftig-forsterking-av-darlige-grunnforhold?publisherId=17847189&releaseId=17916524. GOAL har industripartnere som vil benytte et interdisiplinært team som skal stimulere til datadrevet innovasjon for å transformere jordstabilisering, gjennom kunnskapsutvikling om sensorer, geofysikk, livsløpsanalyser og jordstabilisering. Dette er et utvalg fra en rekke prosjekter som viser at det foreligger kunnskap om hvordan effekter på miljø og klimagassutslipp fra grunnarbeider og fundamenter kan reduseres, og at vi også har metodikk som kan kvantifisere påvirkningen på klima og miljø.

Argumentasjonen "grunnforhold er noe som utbygger ikke har like god kontroll og påvirkning på" kan ikke brukes for at grunnarbeider og fundamenter skal unntas fra kvantifisering av klima og miljøpåvirkning. Kunnskapen om stedegne grunnforhold må og skal fremskaffes før utbygging og byggherrer har et ansvar for å kartlegge grunnen før de velger hvordan tomta skal utnyttes. Dette for å få oversikt over kostnader, behov for konstruksjonssikkerhet, og i tillegg bør dette også brukes til å beregne klima og miljøpåvirkning fra nødvendige grunnarbeider. Dette er vesentlig å synliggjøre i hvilken grad den aktuelle tomten er mer eller mindre egnet for ulike typer utbygging. Ved å kartlegge miljø og klimapåvirkning med mål om å minimere påvirkningen fra grunnarbeider og fundamenter vil det bidra til at det i tidlig fase sette fokus på bærekraftig bygging som kan bidra positivt til å redusere påvirkning fra hele byggeprosessen. Dårlige grunnforhold som krever stor teknisk innsats og ressursbruk for å kunne tilpasses ulike byggverk bør kvantifiseres, også i et klima- og miljøperspektiv.

Videre vil beregning av disse utslippene føre til en bevisstgjøring om størrelsen på utslippene fra grunnarbeider og fundamenter. Den foreslåtte endringen i TEK17 vil bidra til at industrien kvantifiserer og dermed også vurderer ressursforbruk og klimagassutslipp fra bygningskroppen. Dette vil på sikt legge et grunnlag for at klimagassutslipp også tas med som beslutningsgrunnlag for bygg- og anleggsprosjekter, som er helt nødvendig for at Norge skal nå sine klimamål. Det er ingen grunn til at denne prosessen skal forsinkes for grunnarbeider og fundamenter sammenlignet med bygninger.

NGI foreslår at det i forslaget til ny tekst i TEK17 tas inn at beregninger av klima og miljøpåvirkning for grunnarbeider og fundamenter skal gjøres på samme vis som for bygningsdelen. Som for bygningsdelen, bør klimagassregnskapet som minimum inkludere modulene A1-A3 og B4-B5 for bygningselementene angitt i tabell Bygningsdeler. I tillegg bør det for grunnarbeider og fundamenter inkluderes beregninger for modulene A4 og A5 slik at transport til og fra bygningsplass inkluderes. Beregninger vi har gjort viser at transport av masser fra utgraving av byggegrop utgjør en betydelig andel av klimagassutslippene fra grunnarbeider.

Med vennlig hilsen

Lars Andresen
Administrerende direktør
NORGES GEOTEKNISKE INSTITUTT

Guro Grøneng
Guro Grøneng
Områdedirektør
GeoMiljø

Appendix 2

TECHNICAL NOTE: PLAXIS MODEL

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Kopi:	Siamak Feizi
Fra:	Loretta von der Tann
Dato:	2022-08-22
Prosjekt:	Under Oslo - WP4
Sak:	Simplified case study - Plaxis models and input for LCA considerations

Geotechnical design of simplified excavation as input for standardised LCA of geotechnical elements

1 Introduction

The development of standardised processes and elements for geotechnical works in life cycle assessments (LCAs) are yet to mature. To be able to influence individual design decisions, the appropriate information about environmental impact has to be available to engineers in the right detail for the right moment in the design process.
This study aims to look at different design solutions for the same situation to assess if and where there are differences with regard to environmental impacts. Damians et al. (2017), conducted a similar study comparing four different earth retaining wall structures for different heights. In the current study, a simplified excavation situation in a typical Norwegian ground condition is looked at to compare different solutions for the stabilisation of the excavation.

2 System boundaries for LCA

For excavations, most processes are finished once the construction is completed (e.g. for the excavated material the destination might be considered but that happens concurrently with the process of excavation) and the used materials such as steel or concrete often remain in the ground. Whilst a sheet pile wall can in theory be removed to be reused, in Norway this is not usually done as the vibrations would disturb the clay and trigger unwanted settlements. The function of the excavation becomes redundant once the structure within it is built and the space between the structure and the excavation walls is backfilled. As such the system here is looked at until the excavation pit is fully established which can be called "cradle-to-site" or "cradle-to operation" meaning that all the processes are included that are needed to establish the excavation. However, it's worth mentioning that – in Norway – only the lateral support elements (struts and sometimes anchors) are usually taken out or partly taken out. These elements could be considered accordingly which would change the system looked at to "cradle-to-grave" under the assumption that all other material remains in the ground.

Song et al. (2020) suggest a system boundary for geotechnical works in building construction. This boundary includes permanent elements of the building as well as temporary works necessary for establishment of the building but do not serve any function once the building is established (Figure 1, left). In the current study, only the excavation is looked at (Figure 1, right).

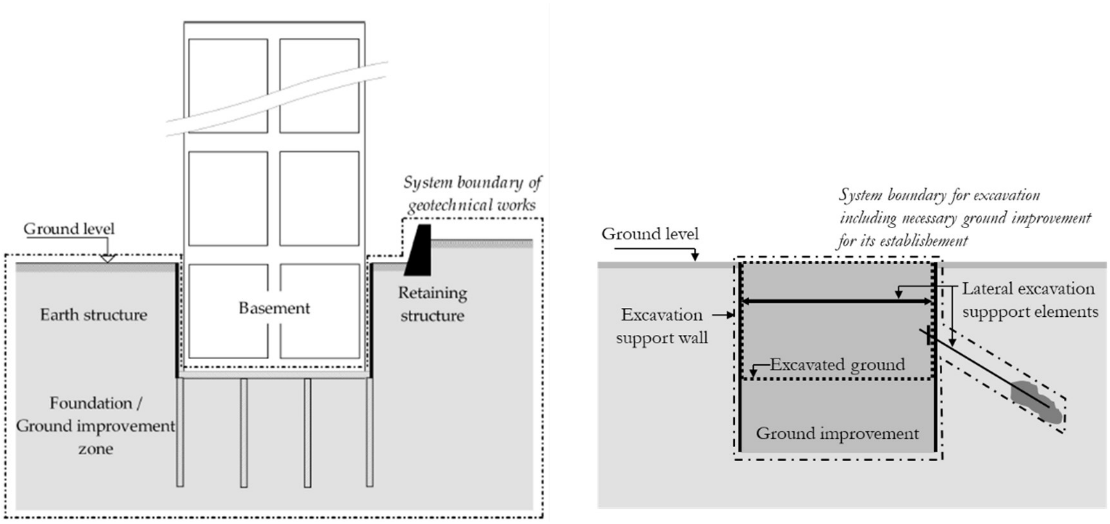

Figure 1. System boundary for geotechnical works connected to building construction as suggested by Song et al. (2021) (left) and in the current study (right).

2.1 Functional unit

The functional unit represents the function of the system studied and provides a reference measure to with the inputs and outputs of the system are then related. The functional unit for the current study is set as "Establishment of 1m running length of an excavation of depth D_e and width W_e in typical Norwegian ground conditions". This is similar to the functional unit used by Damians et al. (2017) who also used 1m running length to compare different retaining structures. It could be refined further by specifying depth and width as well as depth to bedrock and other parameters defined in the next section.

3 Study case set up

3.1 Geometry and ground layers

A sketch of the geometry of the excavation looked at is shown in Figure 2. As mentioned above, the running length of the excavation is not defined, and both, loads and design forces are given per meter. The length of the retaining wall, L, and its profile are two of the main elements to be designed for each case. The ground conditions chosen are typical for Norway, in particular the Oslo area, with a layer of dry crust on top of a thick layer of clay overlying the bedrock. The depth of the dry crust is taken as 2m. The groundwater level is set to 2m below terrain, at the top of the clay layer. The depth to bedrock is set to D_b=25m with an option to vary this depth throughout the study.

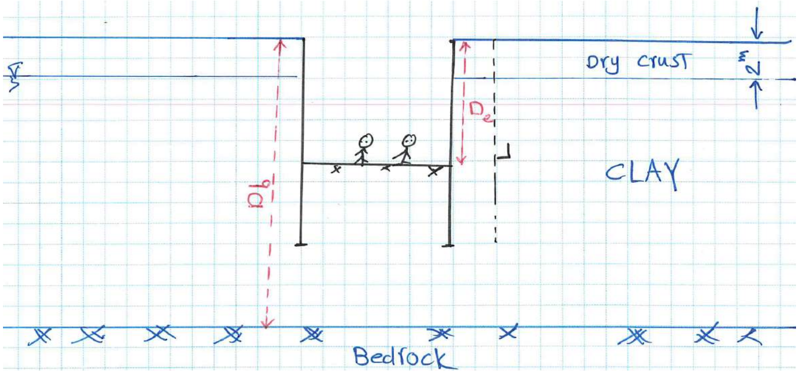

Figure 2. Geometry of excavation for the current study.

The following cases are calculated:

- D_e = 6m with one layer of support at $D_{S,1}$=1m or two layers of support at $D_{S,1}$=1m and $D_{S,2}$=3.5m and
- D_e = 9m two layers of support at $D_{S,1}$=1m and $D_{S,2}$=4.5m (5.5m for anchors) or three layers of support at $D_{S,1}$=1m and $D_{S,2}$=3.5m and $D_{S,3}$=6 m and
- D_e = 12m with three layers of support at $D_{S,1}$=1m and $D_{S,2}$=4.5m and $D_{S,3}$=8 m

The length of the retaining wall, the number of supports and the depth of soil stabilisation below the excavation level are varied and the main parameters of design.

3.2 Design parameters and loads

3.2.1 Undrained soil properties

The clay is modelled using the NGI-ADP model (non-linear, anisotropic, undrained). The characteristic active undrained shear strength c_u^A shown in Figure 3 is chosen to reflect a typical Norwegian clay based on several reference projects. The increase in shear strength in the top meters reflects the observation of a weathered zone underlying the top fill/crust. The parameters used in the PLAXIS model are given in

Table 1.

Because the NGI ADP model does not have a tension cut-off which might result in unrealistic suction at the interface of the sheet pile wall, the earth pressures on the sheet pile wall should be checked for each solution. In case of suction effects, the interface should be modelled as Mohr Coulomb material.

Table 1. Properties used for NGI ADP materials

	Clay to 5m depth	Clay from 5m depth
Drainage type	Undrained (C)	Undrained (C)
γ_{unsat} [kN/m^3]	19	19
γ_{sat} [kN/m^3]	19	19
G_{ur}/S_u^A	700	700
γ_f^C [%]	0.8	0.8
γ_f^E [%]	2.4	2.4
γ_f^{DSS} [%]	1.6	1.6
$S_u^A{}_{ref}$ [kPa]	60	25
γ_{ref} [m]	-2	-5
$S_u^A{}_{inc}$ [kPa]	-11.7	2.2
s_u^P/S_u^A	0.35	0.35
τ_0/S_u^A	0.6	0.6
s_u^{DSS}/S_u^A	0.63	0.63
ν_u	0.495	0.495
R_{inter}	0.6	0.6

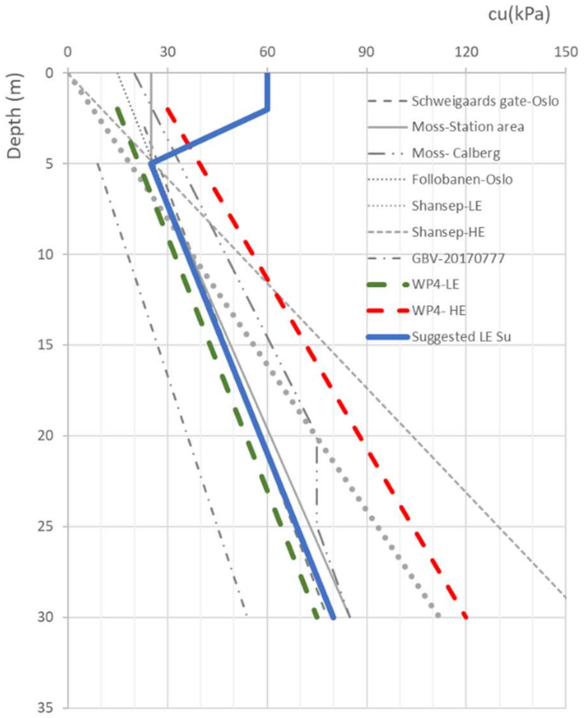

Figure 3. Characteristic active undrained shear strength c_u^A of the clay as a function of depth for several case studies at NGI and as used in the current study case. LE: low estimate, HE: high estimate.

3.2.2 Ground improvement

The ground is assumed to be improved with lime cement columns (LCC) through deep soil mixing (DSM). A certain amount of ground improvement is required to be able to excavate the soft clay. A minimum of 20% stabilisation is here assumed necessary for this purpose. If the LCCs have a static function to support the wall, they have to be constructed in rips perpendicular to the wall. If this is the case, a minimum coverage of 30% is usually required.
The improved soil is modelled as undrained Mohr-Coulomb material and the characteristic undrained shear strength c_u^{LCCa} of the improved soil is here estimated as:

$$c_u^{LCCa} = (1 - a) \times c_u^{clay} + a \times c_u^{cem} \qquad [1]$$

where c_u^{nat} is the undrained shear strength of the natural clay as shown in Figure 3. Characteristic active undrained shear strength c_u^A of the clay as a function of depth for several case studies at NGI and as used in the current study case. LE: low estimate, HE: high estimate., c_u^{cem} is the undrained shear strength of the improved ground, and a is the coverage ratio of LCC stabilisation. An undrained shear strength of c_u^{cem} = 200 kPa is assumed for the stabilised soil below the final excavation level with an assumed lime/cement content of 60 kg/m^3 and c_u^{cem} = 50 kPa above the final excavation level with an assumed lime/cement content of 30 kg/m^3.
The Young's modulus E is estimated in a similar manner with E_{50}^{cem} and The properties of the used materials for different coverages are given in Table 2.

$$E_{50}^{LCCa} = (1 - a) \times E_{50}^{clay} + a \times E_{50}^{cem} \qquad [2]$$

where E_{50}^{clay} is the Young's modulus of the natural clay and E_{50}^{cem} is the Young's modulus of the improved ground, both at 50 % mobilisation. As a lower bound estimate of the Young's modulus of the lime cement improved ground, E_{50}^{cem}, is taken as 50 c_u^{cem}. The Young's modulus of the natural soil is assumed to be E_{50}^{clay} = 21 MPa.
The young modulus increases with confining pressure (and therewith with depth). As a conservative estimate, the rate at which it increases is here set to zero up to a depth of 5m and to $E_{u,inc}$ = 500 kPa/m for the deeper levels. Properties for the LCC materials as modelled in Plaxis are given in Table 2. In general, in the current study, 30% stabilisation is used and only the depth of stabilisation below the excavation depth is varied together with the length of retaining wall. For cases without LCC, it is assumed that still a 20% coverage within the excavated volume is required to facilitate the excavation of the material. As the position of LCCs in this case, however, does not have to fulfil any static requirements, stabilisation for excavation only is not considered in the model.

3.2.3 Drained soil properties

The dry crust is modelled as drained using the Mohr Coulomb model and based on experience values (see Table 2).

Table 2. Properties used for Mohr-Coulomb materials

Parameter	Dry crust	30% LCC (d<5m)	30% LCC (d>5m)	40% LCC (d<5m)	40% LCC (d>5m)	60% LCC (d<5m)	60% LCC (d>5m)
Drainage type	drained	Undrained (C)					
γ_{unsat} [kN/m^3]	19	20	20	20	20	21	21
γ_{sat} [kN/m^3]	19	20	20	20	20	21	21
E [kPa]	15000	32600	32600	32600	32600	38400	38400
ν	0.3	0.3	0.3	0.3	0.3	0.3	0.3
$s_{u,ref}$ [kPa]	-	116	95	116	95	144	130
$E_{u,inc}$ [kPa/m]	-	0	500	0	500	0	500
y_{ref} [m]	-	-2	-5	-2	-5	-2	-5
$s_{u,inc}$ [kPa/m]	-	-7.02	1.32	-7.02	1.32	-4.68	0.88
y_{ref} [m]	-	-	-	-	-	-	-
c'_{ref} [kPa]	1	-	-	-	-	-	-
ϕ [°]	30	-	-	-	-	-	-
ψ [°]	0	-	-	-	-	-	-
R_{inter}	0.7	0.5	0.5	0.5	0.5	0.5	0.5

3.2.4 Structural elements

The sheet pile wall is assumed to be of the type AZ and are modelled as elastoplastic materials. The properties of different AZ-profiles typically used in Norway are given in Table 3. The choice of a specific product is part of the design iteration.

Table 3. Properties of different sheet pile wall sections

	AZ12-770	AZ14-700	AZ17-700	AZ18-700
EI (kNm/m)	3.96E+04	4.66E+04	7.61E+04	7.94E+04
EA (kN/m)	2.58E+06	3.07E+06	2.79E+06	2.92E+06
w (kN/m/m)	0.95	1.13	1.02	1.07
ν	0.28	0.28	0.28	0.28
M_p (kNm/m)	407	563	585	609
N_p (kN/m)	4159	4936	4497	4700

The struts are assumed to be steel pipes with the properties given in Table 4. The properties of possible anchors are given in Table 5. The struts are modelled as elastic and the anchors as elasto-plastic. Here, a 5m spacing for struts and 2.5m spacing for anchors is used. The spacing will not be varied. No prestressing is applied to struts.

Table 4. Properties of struts

Profile (Rør)	355.6/8	406.4/18	508/8	508/10	610/10
Area (mm^2)	8736	10003	12566	15645	18850
EA (kN)	1.83 E+06	2.10E+06	2.64E+6	3.29+06	3.96+06
N_{pl} (kN)	2053	2353	2953	3677	4430

Table 5. Properties of anchors (140 mm^2 strands)

Number of strands	2	3	4	5	6	7
Area (mm^2)	280	420	560	700	840	980
EA (kN)	54'880	82'320	109'760	137'200	164'640	192'080
F_{max} (kN)*	339	508	677	846	1016	1185

*taken from https://geofb.no/wp-content/uploads/2021/12/Datablad-Lissestag-2021.pdf

3.3 Surface loads

A surface load of 10kN/m2 is assumed as a general load covering construction traffic and temporary installations. Loads of e.g. adjacent buildings or infrastructure are not included into the model, as these are very specific to the respective situation and thus would not further inform the question asked here.

3.4 Design requirements and optimization

The excavation should have a safety factor of 1.4 using c-phi reduction for critical stages (the excavation stages) as well as a deformation of the retaining wall below or in the order of 0.5% of the excavation depth. The later requirement is valid for the whole depth of the wall, including the part underneath the deepest excavation level. Engineering judgement can be applied if a deformation is acceptable. For simplification both requirements are applied to the same set of calculations. In real design situations, the deformations would be derived for the serviceability limit state (SLS) with reduced loads compared to the ultimate limit state (ULS).

From experience, often the sheet pile wall is chosen as at least twice the length of excavation depth. Such experience-based requirements for robustness are not taken into account in the current calculations.

The design is optimised to minimise the depth of the sheet pile wall and LCC.

3.5 Limitations

This is a very simplified calculation with the aim to compare different solutions for the same excavation situation. As such, it does not represent any real situation and needs to be treated accordingly. In particular the loads and topography behind the excavation, as well as the ground conditions are likely to be more complex for excavation designs that are actually implemented.

4 Calculation

The calculations are performed as a plane-strain model with the software PLAXIS 2D. The forces in walls, struts and anchors that result from the calculations are characteristic values. Design values are acquired by multiplication with an appropriate load factor.
The tips of the sheet pile walls are either fixed horizontally and vertically to the bedrock or floating when they don't reach the bedrock.
Stuts are modelled as fixed-end anchors, and anchors are modelled as node-to-node anchors in PLAXIS.

4.1 Construction sequence

Calculations are performed for each step of excavation and installation of struts or anchors. In the initial phase a drained hardening soil material is used for the clay. In subsequent steps xxx materials are used. The soil is excavated to 0.5m below an anchor or strut level before the anchor or strut is activated.

1. Initial phase
2. Driving (activation) of sheet pile wall and activation of loads outside of excavation
3. Soil improvement
4. Excavation to level i, 0-5m under strut/anchor level
5. Activation of strut/anchor i

Iteration of steps 4 and 5 depending on number of strut/anchor levels

6. Final Excavation

4.2 Structural elements

To estimate the properties of the lateral support elements in the model, a spacing was assumed. Both, struts and anchors require waling beams for the forces to be distributed along the wall. The assumption for the spacing of struts/anchors directly goes into the design of the waling beam. The struts and waling beams are designed according to Eurocode 3 (NS-EN 1993-1-1:2005+A1:2014+NA:2015). HEB or double HEB profiles are used for the waling beams and HEB's or circular profiles are used for the struts. The sheet pile wall is designed according to Eurocode 3, part 5 (NS-EN 1993-5:2007/NA:2010).

For walls reaching the bedrock, in addition the sheet piles need to be connected to the rock with rock bolts. These are calculated as:

4.3 Model variations

For each of the three excavation depths, two solutions were derived that fulfil both design criteria. In the first solution the soil inside the retaining wall, and the design criteria are met purely by extending the length of the retaining wall. In this case, in the inventory for the LCA, 20% of lime cement stabilisation are taken into account for the excavated clay volume. As mentioned before, this is an experience value of required stabilisation to excavate the soil.

In the second solution, the soil inside the retaining wall is stabilised with lime cement columns (LCC) to the same depth as the retaining wall. A coverage of 30% with LCC is assumed as a minimum coverage to establish structural ribs in front of the retaining wall. For this solution, the number of layers of support is reduced.

The decision for either a longer retaining wall and more support layers or more LCC stabilisation is here considered an individual design decision.

The second such decision looked at is that for an internal strut versus an external anchor. The horizontal forces in the wall will not change depending on that choice, but the anchor introduces an axial force into the sheet pile that has to be accounted for in the design. The decision for anchors will usually mostly depend on the width of excavation – anchors will be chosen if struts are not possible because there is nothing to strut against. For less deep excavations, the wall can also be strutted against the base sla

For deeper excavations/ less deep bedrock than in this first case, it could also be varied if the sheet pile goes all the way to bedrock or is floating. Potentially the second solution requires a higher LCC coverage. Under the argument of "robustness" engineers would likely choose to anchor the sheet pile into the bedrock if the length of the sheet pile does not have to be increased considerably to do so.

5 Results

The purpose of the calculations here performed is to find different design solutions for the same base situation to be able to compare material use with regards to

a) Cost
b) Environmental impact measured mainly in CO_2 emissions and land-use change and calculated using standard processes in SimaPro and a selected number of EPDs.

The use of anchors instead of struts can have an effect on the design of the sheet pile wall as it introduces a normal (vertical) force into the sheet pile wall. Here, the

5.1 Structural points to consider/limitations

The following points have an influence on the design:

- The LCC is assumed as continuous. However, with a coverage of 30%, the continuity in the direction of loading is established through the creation of ribs in that direction meaning that perpendicular to the section as modelled the soil is not stabilised throughout. This might have an influence on the deformations which will probably be larger than modelled here between LCC ribs.

- The designs here are optimised to fulfil the requirements set. However, in geotechnical engineering, often "robust" solutions are sought that build on experience and simplicity of process rather than on the attempt to minimise the use of material. As such, for example a sheet pile will be rarely chosen much shorter than twice the excavation depth and if it is nearly reaching to bedrock, engineers will tend to connect it to the rock, rather than keeping a floating wall just above bedrock.
- In Norway, engineers will also try to avoid using rock anchors wherever possible. This is because through the drilling for rock anchors groundwater can leak into the excavation and lower the pore pressure at bedrock level.
- Temperature effects on the struts have not been considered.

5.2 Model results

Table 6 summarises the model results for three depth and two solutions for each depth. All anchors are modelled at a 45 degree angle.

Table 6. Main forces and resulting structural elements. Solution 2A was not considered for the inventory.

Solution number		**1A**	**1B**	**1C**	**2A**	**2B**	**2C**	**3A**
File name		**6m_ no LCC**	**6m_ LCC 30%**	**6m_LCC_anchor**	**9m no LCC**	**9m LCC**	**9m LCC anchor**	**12 m LCC**
Depth of excavation	m	6	6	6	9	9	9	12
Length of sheet pile wall	m	10	9	10	15	12	18	17
Depth of LCC under final excavation	m	-	3	4	-	6	9	5
Max displacement	mm	24.2	10.4	10.8	216.2	20.7	45.1	29.0
Force strut/ anchor 1	kN/m	49.7	51.5	27.5	46.4	45.3	43.8	45.2
Force strut 2/ anchor 2	kN/m	202.68	-	-	401.9	344.64	98.8	345.5
Force strut 3	kN/m	-	-	-	669.7	-	-	421.0
Force strut 4	kN/m	-	-	-	-	-	-	-
Max bending moment sheet pile	kNm/m	81.7	56.4	51.89	274.7	129.4	189.6	132.6
Max shear sheet pile	kN/m	123.5	59.4	60.44	439.5	194.4	167.7	214.8
Max axial force sheet pile	kN/m	23.3	72.7	92.65	102.1	96.9	218.2	153.3
Sheet pile		AZ12-770	AZ12-770	AZ12-770	A18-700	AZ12-770	AZ12-770	AZ12-770
Profile strut 1/ anchor 1		Rør 323.9x6.3 @5m	Rør 323.9x8 @5m	2x6" @5m 36.6m	Rør 355.6x8 @5m	Rør 323.9x6.3 @5m	2x6" @5m	Rør 323.9x6.3 @5m

Solution number		**1A**	**1B**	**1C**	**2A**	**2B**	**2C**	**3A**
File name		**6m_ no LCC**	**6m_ LCC 30%**	**6m_LCC_anchor**	**9m no LCC**	**9m LCC**	**9m LCC anchor**	**12 m LCC**
Profile strut 2/ anchor 2		Rør 457x8 @5m	-	-	Rør 610x12.5 @5m	Rør 508x12.5 @5m	4x6" @5m	Rør 508x12.5 @5m
Profile strut 3/ anchor 3					Rør 711x12.5 @5m			Rør 610x12.5 @5m
Waler 1		HEB220	HEB220	HEB200 or 2xUNP220	HEB240	HEB220	HEB200 or 2xUNP220	HEB220
Waler 2		HEB360			2x HEB360	2x HEB360 (HEB 550)	HEB280 or 2xUNP300	2x HEB360 (HEB 550)
Waler 3					2x HEB500			2x HEB400 (HEB 600)

6 Inventory for LCA analysis

This section summarises the material use per m excavation for the solutions chosen. An estimate for machine hours for the respective processes will have to be added to be able to model the processes in an LCA. One-off affects such as the transport of machinery is not considered as the contribution of these transports will vary a lot with the length of the excavation. In real situations these should be included. However, the amount of machines to be delivered likely does not differ between alternative solutions for the same situation. The same applies for the amount of excavated soil. Given this is the same for the respective two solutions for the same depth, it is for now excluded of the analysis. Also the backfilling of the excavation outside of the completed structures is not considered. This could be included using the minimal distance between the excavation wall and a building as required in the according regulations.

For the lime cement columns, it is here estimated (experience values) that 60 kg/m^3 of lime cement are needed to achieve the stiffness and strength properties described. In bigger projects more precise values are established through field tests.

Table 7. Inventory of excavated material for different design solutions. All measures are per m running length of excavation

Material	**unit**	**1A**	**1B**	**1C**	**2A**	**2C**	**3A**
Amount of excavated stabilised clay	m^3	96	96	96	144	144	192
	kg	172.8	172.8	172.8	259.2	259.2	345.6

Table 8. Inventory of main materials for different design solutions. All measures are per m running length of excavation. UNP walers are considered for cases 1C and 2C

Material	unit	1A	1B	1C	2A	2C	3A
Steel sheet pile wall	kg	1880	1692	1880	2256	3384	3196
Steel anchor heads	kg	-	-	4.53	-	10.19	-
Steel anchors	kg	-	-		-		-
Steel struts	kg	441.3	157.8	-	647.4	-	1236.2
Steel walings	kg	428	144	104	542	286	966
Cement for lime-cement stabilisation	kg	288	864		1080		1584
Lime for lime-cement stabilisation	kg	288	864		1080		1584
Cement for anchors	kg	-	-		-		-

Machine hours for installation of the sheet pile and LCC as well as excavation are not given.

6.1 Points to keep in mind/consider in the LCA analysis

This note only summarises a first attempt at designing different solutions for the same situation to compare them with regard to impacts following an LCA analysis. However, there are other points to consider that might have a major influence on the impact of the excavation. The following list is a collection of thoughts rather than a comprehensive list:

- There are different binder materials and the choice of binder will likely influence the environmental impact of the construction. A comparison of different binders could be included.
- The destination or use of the excavated masses will also have an influence on the overall impact. In the context of MassOslo (NGI project number 20200466) a simplified LCA is being developed for the handling of masses. There might be potential to integrate this here as well.
- Several machines will be necessary on site: An excavator, a drilling rig for anchors (for those cases with anchors), a rig for driving the sheet piles, and a rig for deep soil mixing for the lime cement stabilisation. A crane for lifting the struts might also be required (or might be done with the excavator).
- It might be appropriate to include a 10cm layer of rough concrete (magerbetong) that provides a clean layer and the basis for foundation works (e.g. drilling rigs) as well as for pouring the concrete of the base slab.
- As has been mentioned before, it could be considered to take into account that few elements (struts, anchor heads, waling beams) are taken out. In addition, the sheet pile wall, if left in the ground, is usually cut at least 1 m under terrain. This

amount of steel, that most probably will go to a recycling facility, could be accounted for.

- The use of anchors is theoretically possible but in general not desirable as the anchors can provide potential leakage points for groundwater from cracks in the bedrock or a shallow moraine layer overlying the bedrock (not modelled here). This can lead to a reduction or pore water pressure at bedrock level and consequently to consolidation settlements in the clay.
- The minimisation of the depth of the sheet pile wall and LCC can lead to high forces in the struts and there might be potential to optimise (see much smaller forces in the anchors due to stiffness reduction).

7 References

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Appendix 3

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First steps in the development of standardised processes for life cycle assessments of geotechnical works

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Abstract. Despite geotechnical works contributing considerably to the environmental impact of buildings and infrastructure, the application of life cycle assessments (LCAs) in geotechnical engineering still needs to be developed and matured. This paper presents a scenario analysis of an excavation in a typical Norwegian geology. For three excavation depths, different design solutions were derived varying the length of the supporting wall and the amount of soil stabilisation within the excavation. The cradle-to-site impacts of the different solutions were then evaluated through a LCA. Global warming and acidification potentials were compared for the different design choices in parallel with an estimate of the respective solution's costs and different functional units were considered. The study shows that, for excavations in the chosen setting, most emissions are caused at product stage and the environmental impact related to the excavated volume or to the additional floor space created underground increases with excavation depth. It emphasises that different impact categories need to be considered to get a full picture of environmental impact. Simple to use LCA tools can provide a direct comparison of different potential solutions. Shifting the focus from minimising cost to minimising environmental impact will likely lead to different design decisions for geotechnical works.

1. Introduction

Geotechnical works are resource intensive and contribute significantly to the environmental impact of buildings and infrastructure. In Norway, a 45% reduction of greenhouse gas emissions by 2030 compared to 2005 levels is intended, with a reduction of 40% required by law [1]. It has been recognized that the construction industry has an important role in the reduction of greenhouse gas emissions, and, for example, the municipality of Oslo has set a target for construction sites to be fossil free by 2030 leading to investments in electric construction machinery across the industry. The consultancy company Asplan Viak has developed an LCA tool (VegLCA) for the Norwegian Public Roads Administration to quantify environmental impacts of Norwegian road and railway projects including geotechnical works [2]. VegLCA is frequently used in practice. Yet, outside of the Norwegian Public Roads Administration the assessment of greenhouse gas emissions and other impact factors is not common practice for geotechnical works and will rarely – if ever – be considered in the design phase. Usually engineering designs of geotechnical works are optimized for safety and, potentially, cost. Considering the above-mentioned targets, it is, however, expected that the focus will shift to environmental performance, in particular greenhouse gas emissions. Consequently, the development and harmonization of assessment tools is more topical than ever.

To make LCAs for geotechnical works feasible and useful, Song et al. [3] emphasised a need for harmonisation of LCA parameters such as functional units, system boundaries and uncertainty analyses and for the establishment of comprehensive life cycle inventory (LCI) databases. Kendall et al. [4] pointed out challenges including data quality and availability as well as comparability between different case studies. The environmental impact of foundations and substructures tends to be neglected in element-based building assessments such as BREEAM because of the dependency of design choices on local conditions and requirements [5]. This is equally the case for excavation works. In Norway, the currently proposed revision of the technical building regulations (TEK17) includes a requirement to account for greenhouse gas emissions for new buildings [7]. Yet, the original proposal that went through consultation in autumn 2021, explicitly excluded groundworks with the argument that the developer does not have control over the ground conditions [8]. In Sweden, a climate declaration has to be prepared for all new buildings and it is suggested that this should include earthworks, even if the methodology how to do so has not been established yet and needs further investigation [9]. In order to collectively work towards a global reduction of environmental impacts from the construction industry, it is essential that resource demanding processes, such as geotechnical groundworks, are included in LCAs. It should also be a goal to harmonize these assessments across countries.

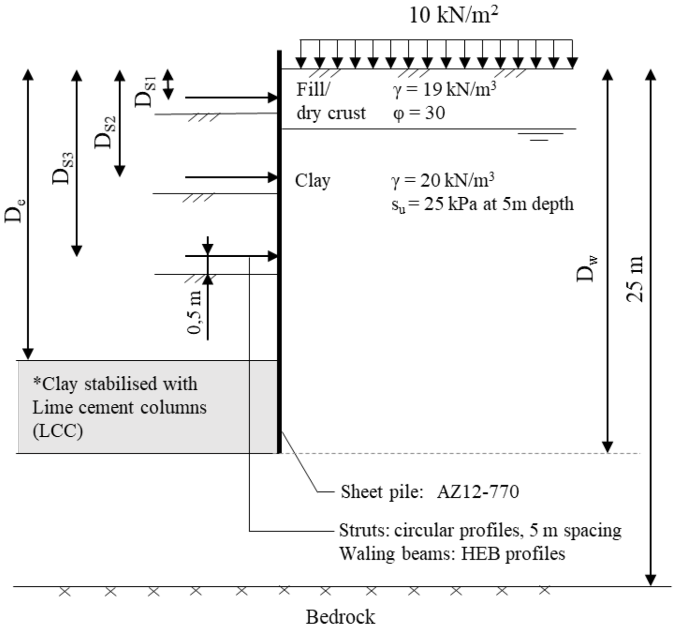
From the design perspective, these discussions are relevant if knowledge about the environmental performance of different, equally feasible solutions would change the decision about which type of, for example, foundation or stability measure will be used in a specific situation. Seol et al. [10] used LCAs to compare different construction methods for urban excavations in Korea. They concluded that consideration of the environmental impact in design would influence the choice of method. However, their study did not report the considered positions in the inventory or data used for the LCA analysis in detail. The current paper presents a scenario analysis for a simplified excavation in a typical Norwegian setting, comparing different design solutions using VegLCA and experience values for cost estimates. The different solutions are related to several different possible functional units. It is further discussed how these environmental impact considerations could be integrated into geotechnical designs and if specific decisions might change if more knowledge and straight forward estimates of environmental performance would be available to the engineer.

2. Methodology: Scenario analysis

To compare the cost and environmental impact of different design solutions, a simple scenario of a 16 m wide excavation in typical Norwegian conditions was analysed and LCAs were performed for different design solutions. The excavations were modelled in Plaxis 2D to obtain dimensions of the support measures which fulfil the considered design requirements (see below). The basic setup is shown in Figure 1. The geology is dominated by a soft clay underlaying 2 m of dry crust. The clay is modelled in two layers to account for higher shear strength in the top layer. The bedrock/firm layer is assumed to be in 25 m depth and the ground water table in 2 m depth. All solutions use sheet pile walls, which is common for this kind of excavation. Three excavation depths of 6, 9, and 12 m were considered. The soft clays in Norway will usually be stabilised for excavation and/or static purposes using lime cement columns (LCC). This is because non-stabilised clays can be difficult to excavate and rips of LCC in front of a sheet pile wall can serve as an internal support of the excavation. For each excavation depth, one solution was derived without considering LCC for static purposes and one with LCC rips in front of the sheet pile wall covering 30% of the excavation area.

The sheet pile wall was supported at depths of 1, 3.5, 6, and 8.5 m for the cases without LCCs and at depths of 1, 4.5 and 8 m for cases with LCC, generally using one support level less if LCCs were considered for static purposes. A typical excavation sequence was followed, excavating to 0.5 m below each support level and then activating the support before excavating to the next level.

As main design requirement, a factor of safety (FoS) of 1.4 was adopted. For real cases, this requirement might vary based on different codes and conditions. Apart from the FoS, a second design requirement was set for the horizontal deformations of the sheet pile wall to stay within a range of maximal 0.5% of the excavation depth. Cases where this was strongly exceeded were discarded as unrealistic design choices.



Case	1	2	3	4	5	6
D_e [m]	6	6	9	9	12	12
D_{S1} [m]	1	1	1	1	1	1
D_{S2} [m]	3.5	-	3.5	4.5	3.5	4.5
D_{S3} [m]	-	-	6	-	6	8
D_{S4} [m]	-	-	-	-	8.5	-
LCC* considered in calculation?	no	yes	no	yes	no	yes

Figure 1. Excavation scenario and list of cases. The excavation depth, D_e, the length of the retaining wall, D_w, and the number and stiffness of struts are varied depending on the case. The soil inside of the sheet pile wall is only stabilised for some of the cases.

2.1. Life Cycle Assessment

To assess the impact of the different scenarios, the life cycle assessment tool VegLCA, version v5.01, was used. The tool builds on the standard specifications for roads in Norway [11]. The main focus of VegLCA is the global warming potential. Other environmental impact indicators such as acidification, eutrophication, photochemical smog and energy can also be evaluated. VegLCA considers the product stage (A1-A3), the construction process stages (A4-A5), the replacement (B4) and refurbishment (B5) stage. Further detail about VegLCA can be found elsewhere [e.g., 2].

This work used the so-called "late phase tool" of VegLCA which was developed for detailed planning phases of infrastructure projects identifying the main processes relevant to the calculated cases that cover geotechnical works typical for deep excavations. The default emission factors, electricity mix and transport distances specified in VegLCA were used.

To estimate the material use for the derived design solutions, an amount of lime-cement of 60 kg/m^3 stabilized soil was considered below the final excavation level where LCC are required for the design (30% coverage). Above the final excavation level, it was assumed that the binder content can be reduced to 30 kg/m^3. For those cases where the LCCs was not considered for statical purposes, a coverage of 20% of the excavated volume with LCCs and a binder content of 30 kg/m^3 were considered. These are experience values that would be used in an early design stage. The following sections describe the system boundaries and functional unit for the LCAs.

2.1.1. System boundaries. For excavations, most processes are finished once the construction is completed. The used materials such as steel or concrete often remain in the ground. Whilst a sheet pile wall can in theory be removed to be reused, in Norway this is not usually done as the vibrations would disturb the clay and trigger unwanted settlements. However, the function of the excavation becomes redundant once the structure within it is built and the space between the structure and the excavation walls is backfilled. As such the system here is looked at until the excavation pit is fully established which can be called "cradle-to-site" including process stages A1-A5 [3]. This includes the excavation and transport of excavated material to landfill or a location where it can be reused. Song et al. [3] suggested a system boundary for geotechnical works in building construction that includes permanent elements of the building as well as temporary works that are necessary for the establishment of the building pit but do not serve any function once the building is established. In the current study, only the latter, the excavation, is considered (Figure 2).

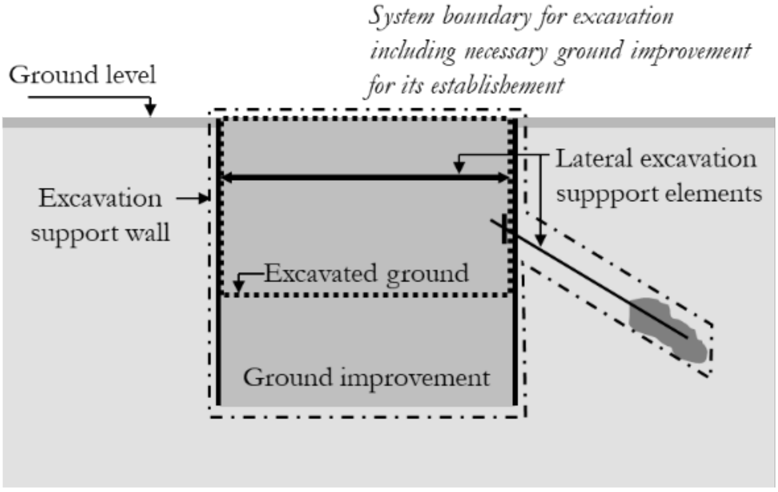


Figure 2. System boundary for geotechnical works as suggested in the current study, based on Song et al. (2020)

2.1.1 Functional unit. The functional unit (FU) represents the function of the system studied and provides a reference measure to which the inputs and outputs of the system are then related. For the current study, the preliminary functional unit was chosen as "establishment of 1 m running length of an excavation of depth D_e and width W_e in typical Norwegian ground conditions". This is similar to the FU used by Damians et al. [6], who also used a FU of 1 m running length to compare different retaining structures. A FU of 1 m running length may be representative for linear infrastructure cases, which are typically modelled using 2D calculations assuming plane strain assumptions. However, different professions might use different FUs. For example, developers frequently adopt the floor space as FU for new building projects [3]. For comparability of cases a more general FU would likely be required. This is explored here by putting the LCA results also in relation to additionally created floor space. Here, only the floor space created underground is considered. The potential of establishing a new FU, relating to the excavated volume, is also discussed.

3. Results

Only the 6 m deep excavation could be designed without lime cement stabilisation. For deeper excavations, stabilisation is required to control wall deformations. Hence, the cases 3 and 5 had to be neglected due to unrealistic wall displacements. As such, only Cases 1, 2, 4 and 6 (Figure 1) were assessed in an LCA. Four main processes were quantified and representative processes chosen in VegLCA. Table 1 lists the processes, the resulting input values and a cost estimate based on experience values. Table 2 lists the quantities of CO_2eq and SO_2eq computed in VegLCA for the four scenarios using internal struts. As specific positions for struts and waling beams are missing in VegLCA, the general position "delivery of steel materials" with the option "reused construction steel" was used. In Table 2, the product and construction stages are summed up, so the table contains stages A1-A5. However, it should be noted that the processes for sheet pile wall and steel delivery in VegLCA focus only on the material production and delivery to construction site (A1-A4). Any emissions from installation of the sheet pile wall are not reported (A5 and direct emissions on construction site).

For the cost estimate, experience values were used that would normally be used for early-stage cost estimates. A steel price of 12 NOK/kg for sheet pile walls, struts, and waling beams was adopted.

Table 1. Derived amounts of materials and cost estimate for four scenarios. The cost estimate is based on experience values

Main process	unit	Case 1	Case 2	Case 4	Case 6
Sheet pile wall*	[m^2]	20	18	24	34
Lime cement stabilisation	[kg]	576	1728	2160	3168
Excavated masses	[m^3]	96	96	144	192
Steel for struts and walers**	[kg]	869	302	1189	2202
Cost estimate	[TNOK]	70	60	104	162
Cost per excavated volume	[NOK/m^3]	730	620	723	1126

* AZ12-770

* Circular profiles for struts, HEB profiles for waling beams

Table 2. Global warming potential and acidification potential of four scenarios with internal struts considering four main processes. The listed emission cover stages A1-A5.

Main process	Case 1		Case 2		Case 4		Case 6	
	kg CO_2eq	kg SO_2eq	kg CO_2eq	kg SO_2eq	kg CO_2eq	kg SO_2eq	kg CO_2eq	kg SO_2eq
Sheet pile wall	1559	4.4	1403	3.9	1871	5.2	2650	7.4
Lime cement stabilisation	563	510	1690	1529	2113	1911	3099	2803
Excavated masses	101	0.3	101	0.3	152	0.4	202	0.5
Steel for struts and walers	1309	4.7	454	1.6	1790	6.4	3315	11.8
Total emission	3532	519	3649	1535	5926	1923	9266	2823
Total emission per m^3 excavated volume	37	5	38	16	41	13	48	15
Total emission per m^2 underground floor space*	110	16	114	48	123	40	145	44

* Assuming 1 floor underground for each 3 m of excavation, not accounting for walls.

Overall, the derived impacts of excavating masses were small compared to the impact of material use (Table 2). The costs per m^3 were similar for depths up to 9 m but significantly higher for a 12 m deep excavation. The global warming potential per m^3 increased by 17% for case 6 compared to case 4. The acidification potential per m^3 remained at a similar scale for all cases using LCC to stabilise the excavation.

Table 1 shows that for the 6 m deep excavations (i.e., cases 1 and 2), the cost for the solution using LCC for statical purposes (i.e., case 2) is estimated to be lower than for the solution where LCCs are not used for statical purposes. This is because an extra support layer is necessary if the LCCs are not considered in the statical model. This difference will increase with increasing steel prices. However, as shown in Table 2, the global warming potential for both cases is similar whereas the acidification potential is much larger for the second case. This is due to LCC stabilisation being the only process that also shows a significant acidification potential. The results for eutrophication potential (kg PO_4^{3-}eq) and photochemical ozone creation potential (kg C_2H_4eq) are not presented here in detail due to space constraints but show a similar picture as the acidification potential.

Figure 3 illustrates how much the four main processes contribute to the global warming potential of the cases analysed. It shows that for cases 3 and 4, the distribution is similar and that for cases 1, 3, and 4 the removeable steel elements contribute more than 30% to the global warming potential. This is relevant insofar, as these elements are here only considered up to the point of construction but will be removed and likely reused.

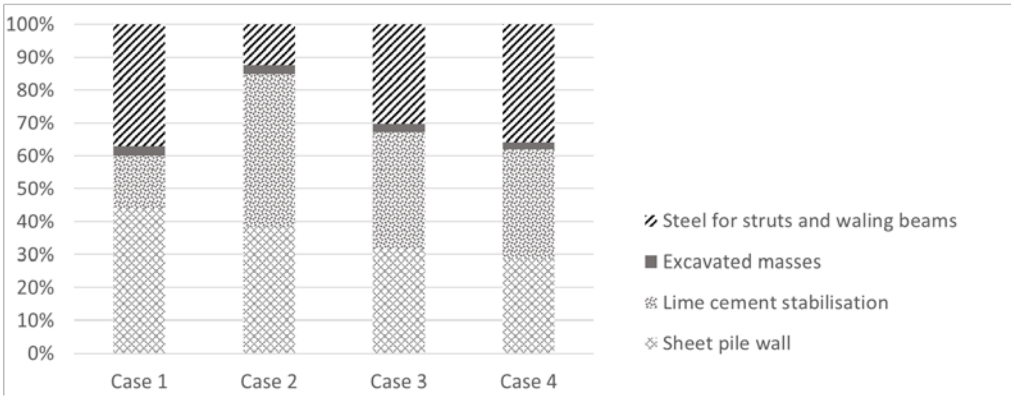


Figure 3. Percentual contribution of the four main processes to the global warming potential of the four cases analysed.

4. Discussion

The analysed scenarios show relatively low emissions caused by the excavation of masses (construction stage) compared to the product stage, suggesting that most emissions caused by earthworks happens at the product stage. These emissions can be reduced on the product level, for example by using recycled steel, or less harmful binders in the soil stabilization process [12]. On the process level, reuse of excavated masses and recovery of the sheet piles could be considered. However, as mentioned before, in the Norwegian soil conditions the sheet piles are usually left in the ground as their removal might cause unwanted settlements in the surroundings. The current paper looked at the potential of emission reduction through design, by choosing the construction method least harmful.

It stands out that lime cement stabilisation contributes significantly not only to the global warming potential but also to other impact categories. Thus, optimising designs to use as little LCC as possible would be desirable. Reducing the analysis to only global warming potential might lead to a false judgement with regards to the environmental performance of a design solution. The presented results thus show the importance of considering multiple impact categories when calculating the environmental impact of geotechnical works. These considerations should also include further development of land-use and soil related impact categories that might be particularly affected by geotechnical works [13].

In geotechnics, engineers will often decide for specific design solutions out of experience. They would also opt for a "robust" design. For example, if a shorter sheet pile would suffice but it's only a few meters to bedrock, engineers would usually choose to extend it to the bedrock. Also, local geological and hydro-geological conditions will influence a design decision. For example, for static purposes anchors could be considered and might be preferred with regard to the spatial organisation of the excavation pit (struts mean a hindrance for excavating the ground). However, in the typical Norwegian conditions, anchors to bedrock also mean a risk for leakage of groundwater from the rock into the excavation. This can lower the ground water table in the bedrock and subsequently in the overlaying clay and lead to settlements of the surroundings over a longer period of time [14].

In addition to the above, contractors often have a certain set of technologies they are familiar with that they might prefer, and additional stabilisation might be required to create safe routes for driving or spaces to place machinery. In an early design stage, which is what is discussed here, there are often uncertainties about the local ground conditions that tend to be captured within the design and are not completely cleared when construction starts. Through continuous monitoring during construction (observational method), temporary elements such as struts can be reduced, but the permanent elements that remain in the ground will be designed so that they cover all possible cases. Simplifications in the designs done here, such as a fixed spacing of struts or the use of a single HEB profile as waling beam would likely not be done for a real design situation, where constructability plays an important role. Overall, design decisions are influenced by a large range of factors that cannot be captured in an LCA.

As might have been expected, the data illustrates that in general less deep excavations will cause less harm and – in a soft clay – an optimization with regard to excavation depth will always be positive. It is also important to remark here that an increase in floor space by building additional floors underground will likely increase the emissions per floor space if earthworks are accounted for. An omission of earthworks in LCA will not capture this effect. A FU relating the environmental impacts of geotechnical works to floor space or excavated volume will enable a meaningful exchange between different experts involved in the project planning and provide a basis for comparison of excavation in different settings and for different purposes.

Apart from defining functional units for geotechnical engineering works, it needs to be evaluated which processes and life cycle stages need to be included in an LCA to appropriately capture the environmental impact from urban excavations. The level of detail of an LCA needs to be inherently connected to the level of detail of the design as the design and construction move along and information about environmental impacts needs to be available at the right point in time and at the right level of detail to adequately inform design decisions. For early design, an LCA tool such as VegLCA that has pre-selected processes (based mostly on EcoInvent) and is simple to use compared to full LCA software programs can provide a direct comparison of different potential solutions. This might shift decisions from cost-optimized to, for example, carbon-optimized solutions. Each decision about an individual project will be influenced by a range of aspects, including project cost and LCA results. How these decisions are taken will depend on the specific setting and likely change with growing environmental awareness. Further and ongoing research is required to understand and optimize these processes.

Including analysis of environmental impact into geotechnical design can facilitate the identification of processes with high impacts on one or several of the environmental indicators that are included in the analysis. These high-impact-processes can be analyzed further to uncover the origin of the impact to the environment. If a hot-spot with a high environmental impact is a material, substitution with alternative materials can be considered. If it is the installation or transportation alternative design solutions can be developed. A targeted and systematic analysis of the environmental impact of the geotechnical design every time the level of detail increases will ensure that the high-impact hot-spots are optimized at each design level. This will also entail a reduction of overall impacts at the local scale.

5. Conclusions

To further the development and understanding of LCAs for geotechnical works, this paper presented a scenario analysis for excavations in typical Norwegian ground conditions. Four cases were analysed varying excavation depth and support elements. For each of the cases, the material use was derived, and cost estimated similar to how would be done at an early design stage. The global warming and acidification potentials were obtained for each case through a simplified LCA analysis using VegLCA for only the four main processes identified.

The data showed that, for the chosen setting, most emissions caused by an excavation are caused at product stage. The global warming potential per m^3 increased with excavation depth whilst the acidification potential per m^3 remained at a similar scale for all cases using LCC to stabilise the excavation. Agreeing on a FU such as the excavated volume or to the additional floor space created underground will enable standardized reporting and facilitate comparative studies between different settings and projects. In that, not only global warming potential should be considered as major environmental impacts might be omitted.

The first choice of construction method when designing an excavation is often based on experience rather than on a comparative analysis of different possibilities. In addition, unforeseen site conditions, availability of materials, or operational requirements mean that what is built can differ considerably from what is planned in an early design stage. However, simple to use LCA tools can provide a direct comparison of different potential solutions and promote continuous learning about the environmental impact of geotechnical works. This will not only change design considerations within the geotechnical profession but also the conversation between different disciplines involved in a project and ultimately further a shift towards more environmentally friendly project design.

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Appendix 4

DTU-STUDENT REPORT: LIFE CYCLE ASSESSMENT: EXCAVATION PIT OF THE LIFE SCIENCE BUILDING OF THE UNIVERSITY OF OSLO

42372 - LIFE CYCLE ASSESSMENT OF PRODUCTS AND SYSTEMS

Life Cycle Assessment
Excavation Pit of the Life Science Building of the University of Oslo

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Preface

The underlying report is performed as a group assessment in the course "42372 - Life Cycle Assessment of products and systems" at the Technical University of Denmark (DTU). The objective is to conduct a Life Cycle Assessment (LCA) to evaluate the environmental impacts of the geotechnical works of the Life Science Building (LVB) of the University of Oslo. The commissioner of the study was the Norwegian Geotechnical Institute (NGI), while the report was delivered by five students. The group were supported by the Teaching Team and Teaching Assistants for LCA expertise as well as by NGI for technical background on groundworks and data for the specific construction site.

Report Contribution:

At the request of the course, a list of each member's contribution is presented. It should be noted that all the work presented here has been carried out with the collaboration and agreement of all the members of the team, especially as far as important decisions are concerned.

Dhruv Sharma - s210122: SimaPro Model, Introduction (1.1), Goal definition (2.1), Scope definition (3.4, 3.6), Life Cycle Inventory Analysis (4.7), Interpretation and Discussion of results and uncertainties (6.1, 6.2, 6.3, 6.4.2), Conclusion, Limitations and Recommendations (7.2, 7.3)

Rémi Villain - s212833: SimaPro Model, Goal definition (2.5), Scope definition (3.6, 3.7), Life Cycle Inventory Analysis (4.7), Interpretation and Discussion of results and uncertainties (6.1, 6.2 6.3, 6.4.2), Conclusion, Limitations and Recommendations (7.3).

María Sancho López - s172239: Technical Summary, Goal definition (2.2, 2.4), Scope Definition (3.2, 3.3, 3.5, 3.9), Life Cycle Inventory Analysis (4.3, 4.4, 4.7.1), Life Cycle Impact Assessment (5.1, 5.1.1, 5.1.2), Conclusion, Limitation and Recommendations (7.1).

Raphael Minis - s203346: External communications, Introduction (1., 1.2, 1.3, 1.3, 1.5), Goal definition (2, 2.2, 2.3), Scope definition (3, 3.1), Life Cycle Inventory Analysis (4.1, 4.2, 4.3, 4.4, 4.6), Life Cycle Impact Assessment (5.,5.2), Interpretation and Discussion of results and uncertainties (6.)

Fides Hensel - s202610: Goal definition (2.6), Scope definition (3.2, 3.7, 3.8), Life Cycle Inventory Analysis (4.3, 4.5, 4.7), Life Cycle Impact Assessment (5.1.3), Interpretation and Discussion of results and uncertainties (6.2, 6.4.1, 6.4.2), Calculation of Sensitivity analysis, Conclusion, Limitations and Recommendations (7.1, 7.2, 7.3)

Raphael Minis

Executive Summary

The underlying report analyses the environmental impacts of the geotechnical works on the Life Science Building (LVB), a current construction project for the University of Oslo for education, research and hospital purposes. The impact analysis is performed with the help of LCA methodology and follows the guidelines of ISO 14040. The study is commissioned by the Norwegian Geotechnical Institute (NGI), who is consulting within the construction project and performed by a student group of the DTU course "42372 - Life Cycle Assessment of products and systems". The objective for NGI is to gain knowledge and experience on LCAs within groundworks as well as getting insights in the most contributing processes within the specific part of the construction project. Hence, no direct decision is based up on this study.

The construction site at the LVB has a big challenge; a unstable clay, which turns into a fluid when putting to much load on it, a so called quick clay. This results in big and resourceful efforts to stabilize the soil and the foundation. The study is done in a cradle-to-site manner, meaning that the raw materials and the production phase are included, while the use phase of the assessed product as well as the disposal phase has been neglected. In terms of the construction of the building, only the geotechnical works are included in this LCA. This means more specific, that the establishment of the excavation pit as well as the foundation set up is included. Excluded are all processes, which follow after the foundation and would rather be part of the actual building process than part of the safeguarding of the construction. Therefore, the following functional unit (quantitative and qualitative description of the product system) were defined: Creating and safeguarding an excavated volume of earth of 206,000 m^3[11] in quick clay to support the Life Science building (LVB), a construction with a gross floor area of 17,000 m^2[11] and a lifetime of 50 years in Oslo (Norway), according to all required standards.

The needed information for conducting this analysis, such as background knowledge about the different processes as well as amounts and specification of material used was partly provided by NGI. In order to complete the study, all missing data, whether amounts, type of material or other were assumed with reasonable sources. Further, pre-modelled processes within the used LCA software, SimaPro, as well as the chosen database, Ecoinvent, were used when no specific or better information was available. Specific information about this can be found in section 4.5.1 and 6.4.1.

Following from this, the major limitation of this study is the simplifying complexity of the real world product system. This includes the concentration of the main tasks and not the 100% measurement of every action at the construction site, but more over the generalization with pre-modelled unit processes and assumptions. All limitations in a extended approach can be found in chapter 7.2.

With respect to the limitations, of the study and especially the created model the hotspot of the assessed product system can be claimed to be the process of "Steel Core Piles" (part of the foundation in order to secure the ground floor slab). Specifically, the use of steel (amount and especially the type) can be pointed as the main environmental impact driver of the groundworks of the LVB. Impact-wise, this mostly affects the impact categories "fresh water ecotoxicity" and "ozone layer formation (human health)". Further and more general, the highest impacts in the establishment of the foundation of the LVB, are steel and cement from the unit processess "Steel Core Pile" and "Soil Stabilization" respectively, both in the before mentioned steel core piles but also in other processes. This worsen especially the previous mentioned impact categories.

Following from this, research should be continued to come up with less limitated results. In this respect, contact to the steel and cement producer has been made in order to improve the representativeness of the Life Cycle Inventory by including specific background data of the processes. Unfortunately, no additional information was provided until the submission of this report. Due to the aim of identifying the hotspots of the product system, further work could also concentrate on the impact reduction. This could be done, due to the change to less impactful materials or using the same materials done by new and advanced technology, including less environmental impact overall. A extended overview about the recommendations and explanations can be found in section 7.3.

Technical Summary

The Norwegian Geotechnical Institute (NGI) is supervising the groundworks of the Building of Life Sciences (LVB) for the University of Oslo in Oslo, Norway. Because of the special characteristics of the soil in the city of Oslo and the magnitude of the project, the groundworks are a very important part of the construction and many project resources are intended for this purpose. NGI wishes to assess the overall environmental impacts that groundworks have had and identify which are the most contributing areas and processes with the ambition to optimize future projects.

To fulfill that purpose, a life cycle assessment (LCA) was conducted with the following goals: (i) assess the current environmental impact of the groundworks involved in the establishment of the excavation pit, (ii) identify which are the most contributing processes and why, (iii) gain knowledge about the practice of conducting an LCA on groundworks. The deliverables include: (i) life cycle inventory (LCI) of different processes, (ii) life cycle impact assessment (LCIA) results (in both characterised and normalised forms and for midpoint and endpoint impact categories) and (iii) process and substance contribution analysis. The functional unit that has been defined to carry out the study is: *Creating and safeguarding an excavated volume of earth of 206,000 m^3[11] in quick clay to support the Life Science building (LVB), a construction with a gross floor area of 17,000 m^2[11] and a lifetime of 50 years in Oslo (Norway), according to all required standards.*, and all calculations have been made for a reference flow of one excavation pit.

The system boundaries has been set on the raw material and the production phases (creating and setting up the excavation pit), which compromises from cradle-to-site processes. The processes that have been analyzed are: (i) excavation of masses, (ii) soil stabilization, (iii) sheet pile wall, (iv) steel core piles, (v) anchoring of sheet pile wall, (vi) ground floor slab. The data that has been used to build the LCI of these processes comes mainly from NGI, which in turn comes from the different contractors and service suppliers. In the cases where no primary data could be retrieved from the suppliers, Ecoinvent 2010 database [21] has been used. Further, assumptions were made where data was missing. Major assumptions were made when modelling some of the unit processes, and that has translated to an overall medium level of representativeness. The study has been carried out under the assumption that the technology and materials of the groundworks are on the current technology level and would not significantly change in the near future. The analysis has been created under the assumption that the material production and delivery mainly would take place in Europe.

The results show significant differences between the impact of the studied processes. The most contributing process has been disclosed to be clearly steel core piles, which account for the biggest impact in most of the categories studied both for midpoint and endpoint analyses. Contributing more than 60% to marine eutrophication, freshwater ecotoxicity, human carcinogenic toxicity,mineral resource scarcity and water consumption, and being the process that contributed the most to all impact categories except for land use (after soil stabilization), terrestrial ecotoxicity (after excavation of masses) and ionizing radiation (where it has a positive impact). Then, the second most contributing process is sheet pile wall, which accounts for between 20% and 30% in various impact categories: fine particulate matter formation, terrestrial acidification, freshwater eutrophication, marine eutrophication, freshwater ecotoxicity, marine ecotoxicity, human carcinogenic toxicity, human non-carcinogenic toxicity, mineral resource scarcity, fossil resource scarcity and water consumption. Further, the sheet pile wall is the smallest contributor in stratospheric ozone depletion and land use. After these two, the ranking of most contributing processes continues with soil stabilization, excavation of masses, anchoring and, finally, ground floor slab.

There results together with the subsequent analysis and checks have resulted in the following main conclusions:

I. In the establishment of the LVB excavation pit, the process with the significantly biggest environmental impact throughout midpoint and endpoint impact categories are steel core piles. It is therefore identified as environmental hotspot of the analyzed process system.

II. There is a clear hierarchy in terms of which processes are more impactful and that is: steel core piles, sheet pile wall, soil stabilization, excavation of masses, anchoring of sheet pile wall and ground floor slab. How significant is the difference between each process in total terms has been discussed in section 6.

III. Regarding substances contribution, global warming impacts are mainly driven by emissions of carbon dioxide (CO2), which contributes to 90% of the total impacts. The biggest contribution processes to CO2 emissions are steel core piles (44%) and soil stabilization (22%). Terrestrial toxicity as well as freshwater and marine ecotoxicity are the most impacted by copper (around 50%), which comes mainly from steel core piles and sheet pile wall processes. Regarding mineral and fossil resource scarcity, iron and nickel and coal and oil are the most impactful substances respectively.

IV. The external normalization performed for the midpoint results show that the results are in an order of magnitude that is reasonable with the magnitude of the analysed reference flow of one excavation pit.

V. From the weighted results in terms of the three endpoint impact categories, it is distinct that human health is most impacted, with a total impact which counts for 95% of the total impact. The Ecosystem is impacted 3.8% of total impact and the resources are following with 2%. This distribution of the impacts is very similar across all analysed processes, however the magnitude of the impacts is different and follows the previously described hierarchy.

VI. The overall environmental performance of steel core piles is mainly determined by the type of steel used in production stage. It has an extreme variable impact on freshwater ecotoxicity and ozone formation/human health. It therefore can be considered an important environmental performance indicator for the LVB excavation pit.

VII. The type of steel and amount used in steel core piles, in Sheet Pile walls as well as the type of cement and amount used in soil stabilisation are important environmental key parameters are the most sensitive parameters. They have significant impact on impact categories "Ozone formation/human health" and "Freshwater ecotoxicity" respectively.

VIII. The ground-floor slab is the least environmentally impactful process in the comparison of processes needed for the establishment of the LVB excavation pit, but is also the least representative process Table 6.

In the following, broad recommendations based on the conclusions of the report are presented.

The major takeaway is that the type and amount of steel used in the process "Steel Core Piles" have the most significant overall environmental impact and thus present the biggest opportunity for lowering it. As the analysis has shown, the amount of steel has significant influence on particular matter formation and human carcinogenic toxicity. It can therefore be recommended to focus on the optimization efforts on the amount of steel used in the process Steel core piles keeping in mind the regulatory and safety standards in construction industry.

As for the amount of steel in steel core piles, the type of steel is also sensitive to freshwater eutrophication and affecting the endpoint ecosystem. Furthermore it affects the impact category ozone formation, which accounts to the endpoint of human health. One of the major takeaways is that the impact category freshwater eutrophication is being affected the most irrespective of the steel type used in the model.

Possible recommendations for reducing the environmental impact of steel used in steel core piles are:

1. The reduction of the amount of steel used. This could be achieved by changing the thickness of the casings used, while maintaining the technical requirements and safety standards.
2. A change in the type of steel used. This could entail using a higher share of recycled steel or steel produced using a more sustainable production process, which uses less energy intensive. However, since the current model assumes steel production based on a European mix of electricity and heat production (most efficient currently), the potential for optimization in this point is questionable.

From the scenario analysis of the type of cement in the unit process soil stabilisation, it was determined that the most impacted category is freshwater eutrophication (Figure 17). It is recommended to use a type of cement which has less impact on freshwater ecotoxicity. The results might change when the actual percentage of type of raw material used in Multicement is implemented in SimaPro, since the material has a lower carbon footprint compared to traditionally produced materials [22].

As the analysis of the sheet pile walls process has shown, neither the amount of steel nor the type of steel used in this process has significant environmental impact. So, it is not a priority to change anything in this respect for this unit process.

Contents

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1 Introduction

Sustainable Development, in all three pillars - Social, Environmental and Economical - is one of the biggest challenges in today's society. While the UN sets and agrees on the 17 Sustainable Development Goals (SDGs), the EU is setting the Green Deal and countries decree on carbon goals, a lot of companies are trying to perform more sustainable. In order to be sure they are developing their products in the right, mostly environmental, direction, the tool of Life Cycle Assessment (LCA) was created. It is a technique for assessing the environmental aspects and potential impacts associated with a product or service over its entire life cycle [1]. In this report, a LCA of a service has been performed, which is the setting up of an excavation pit. The excavation pit has been set up as part of the construction for the Life Science Building of the University of Oslo in Norway [13]. The study has been commissioned by the Norwegian Geotechnical Institute (NGI). Before diving into the specifics of the study, within the introduction, a common base is set by presenting the background of the study. Therefore, in section 1.1, information about LCAs in the construction and especially of ground-works is presented. Further, the objective of the report (section 1.2) is defined, before the NGI (section 1.3) as well as the specific construction site (section 1.4) is introduced. Finally, the structure of this report (section 1.5) is given.

1.1 Theoretical Introduction to Life Cycle Assessment within the building sector

The building and construction sector accounts for huge amounts of carbon emissions and natural resource utilization. Within the European Union (EU), the buildings account for the largest share of the total amount of extracted materials (50%) and final energy consumption (42%), and cause about 35% of all greenhouse gas (GHG) emissions [2]. Traditionally, the most of the LCA studies has been carried to analyse the environmental impacts of operational stage of the buildings in relation to the energy efficiency [3][8]. In this study, the environmental impacts from the geotechnical works to set up the excavation pit for the building have been performed.

Geo-technical works and their related processes take place at the early stage of the construction of building. Most of the processes (soil stabilization, steel core piles installation, sheet pile wall etc.) are often energy and resource intensive. So, to optimize the resource usage and to find the potential ways in which the conventional construction techniques of geotechnical works can be improved, it is vital to identify the areas which are highly impactful [11].

In recent literature, there are noticeable discrepancies on LCA of buildings, especially regarding functional units, system boundaries, impact categories, and uncertainty/sensitivity analysis of LCA results [8]. This can be due to the fact that geotechnical works do not have any legal constraints to be included in the LCA of the building. Hence, LCA studies on groundworks are generally not performed, the available research is limited and there are no established guidelines yet [11][8].

As a reference for this study, the approach suggested by Song [8] will be followed with minor modifications due to the specific interests of the commissioner of the study. That is that the product will be defined as the substructure of the building [9], excluding temporary geotechnical works and the basement but including the ground slab as requested by NGI. It is also imperative to mention that the LCA on groundworks is very location dependant and therefore it is particularly difficult to objectively perform comparisons with other reports. A careful consideration of the functional unit (especially referring to parameters such as type of soil, bedrock's depth etc. . .) is necessary considering the nature of the study if the results are to be used for any kind of comparison [8].

Because this LCA study is part of a research program on groundworks, the reader should be made aware that its main value does not lie in the quantitative results from the LCA, but rather in the process of building a LCA methodology adapted to groundworks.

1.2 Objective of the report

The objective of this report is the evaluation of environmental impacts of the geotechnical works of the Life Science Building of the University of Oslo. This is carried out with the application of LCA methodology.

1.3 Introduction to the Case company the Norwegian Geotechnical Institute

The Norwegian Geotechnical Institute (NGI) is the case company to the student group of DTU, who is carrying out this report. NGI is a independent international centre for geotechnical expertise, where research and engineering-realated services in geosciences are focused. Founded in 1953 as a state owned research institute, it changed to an independent and commercial company in 1985. Today, the company is based with its head office in Oslo and further subsidiaries in Trondheim (both Norway), Houston (USA) and Perth (Australia). NGI strives to provide knowledge to solve challenges on- and off-shore around the environment, energy and natural hazards. One part of the activities is the consulting in construction projects to ensure a safe and long lifetime. In NGIs consulting services it is common to create solutions for the owner of a building site, to enable that a contractor can safely operate. One of the current focus of NGI is the project called "Under Oslo", which investigates "innovative methods, sustainability and economic considerations when building below the surface". Within this research endeavor, Work-package 4 focuses on sustainability and aims to support the research around the sustainability assessments of construction works. A major part of that is the quantification of environmental impacts.

1.4 Introduction to the specific construction site

As mentioned above, the object of assessment are the geotechnical works of the Life Science Building of the University of Oslo. This building will be part of the university and used for education and hospital services, containing teaching and research facilities, as auditoriums and laboratories as well as research and office areas. Therefore, the laid out concept plans to host up to 1000 university and 600 hospital employees as well as up to 1500 students. While the planning started in 2014, the completion is currently set for 2026. The excavation pit of the building which is part of the underlying LCA was finished by the mid of 2021, whereas the second part of the geotechnical works, the foundation is still currently under construction. The Life Science building is planned to have a gross floor area of 17,000 m^2 and a gross building area of around 97,000m^2. A animation of the expected result of the construction work can be seen below in figure 1 [11][12][13].

Figure 1: Animation of the Life Science Building of the University of Oslo [14]

1.5 Structure of the report

The report starts with the goal (section 2) and the scope (section 3) definition, which are the first two elements of a life cycle assessment framework. These are very important as a foundation for the interpretation and further application of the respective results. Further, in chapter 4, the Life Cycle Inventory Analysis (LCI) of the underlying assessment is described, where the process for the collection as well as the actual data is analysed. In Section 5, the Life Cycle Impact Assessment (Section 5), with the results of the quantitative assessment is presented. This is followed by the interpretation and discussion of the results (Section 6) as well as setting these in relation within the sensitivity analysis. Finally, the report is completed with the conclusion of the results of the LCA (section 7.2.

2 Goal definition

Within the following section the aim for the underlying LCA is specified. This helps to interpret and use the results of this study. First, the intended applications are specified (section 2.1), before the limitations of this study are displayed in section 2.2. Further, the reasons for this study is explained (chapter 2.3) as well as the target audience of the outcomes of this study (section 2.4). Finally in the goal definition, it is stated if this study is from a comparative nature and who the study was commissioned by.

2.1 Intended applications of the deliverables / results

The intention of the LCA study is to gain knowledge about the current environmental impact of the geotechnical processes involved in the excavation pit using hotspot analysis. The study will not be used as a decision tool to bring major changes in the execution of geotechnical works involved in this very excavation pit. However, this information could potentially be used in the future for optimization of the highly impactful processes.

2.2 Limitations due to the method, assumptions, and impact coverage

Within this project, an environmental LCA is been done, where only environmental criteria are assessed. Therefore, societal and economic impacts are not covered and also not included in the final results and conclusions.

A major limitation factor is a consequence of the chosen system boundaries in this study: cradle-to-site (explained in more detail in section 3.4).This choice was made because of the uncertainties related to the end of life of the system and because the impact related to the use phase was considered to be negligible compared to the extraction and production phase for this study.

Regarding geotechnical works, the most relevant flows in the process of establishing an excavation pit are analysed. However some processes were not considered in this study due to specific reasons, which are further explained in section 4.1. Further limitations were identified within the usage of this study results, as they are only intended for internal use and should also not be used for comparison of two systems.

2.3 Reasons for carrying out the study and decision-context

The LCA study on the LVB excavation pit is of no commercial interest, but about gaining knowledge and getting an overview of the impacts of the excavation pit as this study is part of the R&D program “Under Oslo” of the Norwegian Geotechnical Institute (NGI).

From our study direct decisions will not be made. Further, within the assessed system interactions with other systems are happening and therefore system expansion at least from the used LCA software is expected. As a conclusion, the decision context, based on ILCD recommendations, can be defined as C1 [10].

2.4 Target audience of the deliverables / results

The deliverables will be presented to NGI and the involved stakeholders: the design and construction partners (e.g., the contractor HENT) as well as the owner of the construction site (Statsbygg).

2.5 Comparative studies to be disclosed to the public

The LCA study is not carried out as a comparative analysis (e.g., with another excavation pit using dissimilar materials or geotechnical technologies) but will identify the process with the highest contribution to the total environmental impact within the product system (hotspot analysis). It is a non-comparative study, and it will not be disclosed to the public but results might get published later by NGI.

2.6 Commissioner of the study and other influential actors

The study is conducted by a group of five students of the course “42372 Life Cycle Assessment of Products and Systems” at the Technical University of Denmark (DTU). The commissioner of the LCA is NGI.

3 Scope definition

In this section it is determined what product systems are to be assessed and how this assessment should take place. The scope definitions consists of nine main steps: 3.1 Deliverables, 3.2 Object of assessment, 3.3 LCI modelling framework and handling of multifunctional processes, 3.4 System boundaries and completeness requirements, 3.5 Representativeness of LCI data, 3.6 Preparing the basis for the impact assessment, 3.7 Special requirements for system comparisons, 3.8 Critical review needs and 3.9 Planning reporting of results, which will be presented in detail.

3.1 Types of deliverables, in line with intended applications

The LCA study should result in a Life Cycle Inventory (LCI) (section 4) and an Life Cycle Impact Assessment (LCIA) (chapter 5). The latter should contain the midpoint (section 5.1) and endpoint (section 5.2) results each with the characterized, normalized and weighted results. Further, also the process and substance contribution can be found in chapter 5.1. The report contains the unit process study, the interpretation, discussion and conclusion of the results. Further, it also analyse the completeness, uncertainty, and validity of the specific and modelled system.

3.2 Object of the assessment - system/process studied with functions

The object of the assessment is the life cycle impact of an excavation pit. In terms of the building structure, this represents the geotechnical works which are being considered in this study, as it can be seen in figure 2.

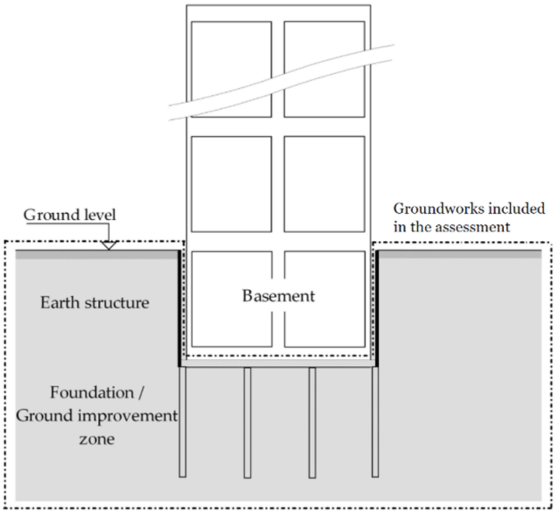


Figure 2: Groundworks included in the assessment. Modified figure [8]

Specifically, the following major processes of the product system could be identified:

1. Site Investigation
2. Soil Stabilisation
3. Establishment of Sheet Pile Wall (Further referred as Sheet Pile Wall)
4. Anchoring of sheet pile wall (Further referred as Anchoring)
5. Excavation of masses
6. Steel Core Piles (building is founded on piles)
7. Ground Floor Slab
8. Earthworks (refilling, etc.)

3.2.1 Functions

The function of an excavation pit is it to enable the building process of a building and to secure the stabilization of the building.

3.2.2 Functional unit

Creating and safeguarding an excavated volume of earth of 206,000 m^3[11] in quick clay to support the Life Science building (LVB), a construction with a gross floor area of 17,000 m^2[11] and a lifetime of 50 years in Oslo (Norway), according to all required standards.

3.2.3 Reference flows

To fulfil the functional unit, we require to set up one excavation pit per building.

3.3 LCI modelling framework and handling of multifunctional processes

Within this study an attributional LCA will be carried out. No multi-functional processes have been identified in the system.

3.4 System boundaries, completeness requirements, and related cut-off rules

The product system of the excavation pit has four steps, beginning with the raw materials, setting up the excavation pit (production), to the use and disposal stage. For the scope of the upcoming study the system boundaries will be on the raw material and the production (creating and setting up the excavation pit) of the product. The use stage of the excavation pit is disregarded as its environmental impact was decided to be negligible in the meeting with NGI. Due to the uncertainty on possibilities of reuse or disposal of the excavation pit in the future, the disposal stage was disregarded. The explained system and boundaries can also be seen in the figure below. This LCA follows therefore a “cradle-to-site” approach (Hauschild, 2018). As mentioned earlier, in section 2.2, within the production stage of the analysed system there are processes which will not be covered in this study. These processes are the site investigation and the earthworks. Both of these contributions to the system were not be included in this study as details were not be delivered by NGI. Further, due to the nature of these processes and a expected marginal impact on the environment (from the experts of the case company NGI) it was decided to neglect these two parts.

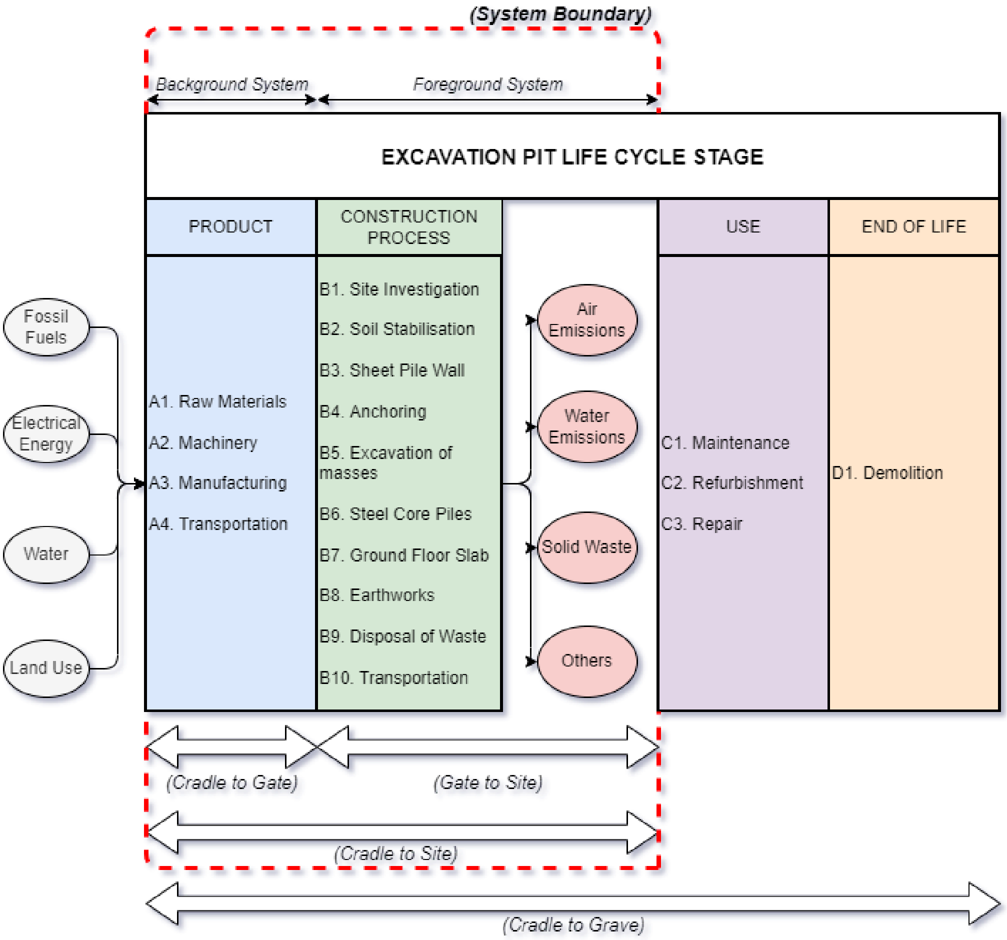


Figure 3: System Boundaries of the underlying LCA

3.5 Representativeness and appropriateness of LCI data

The included processes within the underlying LCA are representative for the city of Oslo, Norway, the year 2021 and the current available technology. A detailed description can be found below.

Technological representativeness The material, production and manufacturing technology for all processes, should represent the technology that is currently used by HENT (construction company) and its primary material suppliers. It is characterised by being a relatively high efficiency technology due to the use of new machines and modern processes. Thus, the data for the groundworks should mainly come from HENT and its suppliers. In case data is missing, other Scandinavian and European processes should be used.

Geographical representativeness. Regarding geographical representativenesss, the materials used in the different processes should represent the extraction and manufacturing in Scandinavia or Europe as shown in table 1. Some processes such us LC columns, excavation of masses or building the ground slab, take place entirely in the construction site in Oslo. In other processes, elements manufactured in Scandinavia or Europe are installed. All the assembly takes place in the construction site in Oslo.

Table 1: Scope of geographical representativeness

Stage	Process in excavation pit					
	Soil Stabilisation	**Excavation of masses**	**Anchoring**	**Sheet Pile Walls**	**Steel Core Piles**	**Ground Floor Slab**
Materials			Steel: Scandinavia, Europe			
	Cement: Scandinavia, Europe					
					Concrete: Scandinavia, Europe	
						Lean concrete: Scandinavia, Europe
Manufacturing	LC columns: Oslo, Norway	Excavation of masses: Oslo, Norway	Anchors: Scandinavia, Europe	Sheet pile walls: Scandinavia, Europe	Steel core piles: Scandinavia, Europe	Concrete deposition: Oslo, Norway Oslo, Norway
	Other elements: mainly Europe	Other elements: mainly Europe	Other elements: mainly Europe	Other elements: mainly Europe	Other elements: mainly Europe	Other elements: mainly Europe
	Assembly: Norway, Oslo					

Temporal representativeness: The data should also represent the time when the processes took place. The ground works for the LVB take place between 2019 and 2022, while the overall building is planned to be finished by 2026, as shown in figure 4. Thus, all the processes should be modelled with data representative of this time period.

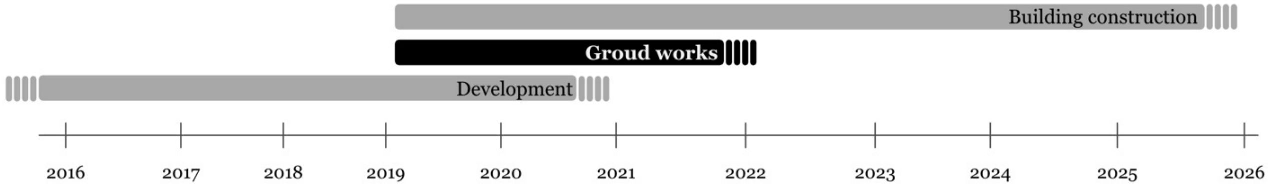


Figure 4: Temporal scope of the Life Science Building (own graphic with information from [15] & [12]

3.6 Preparing the Basis for the Impact Assessment

The impact assessment has been performed using the software "SimaPro". The perspective of the impact assessment has been chosen as "Hierarchical", as it is time scope is balanced and it looks between long and short term impacts. With this perspective, right policy implementations can avoid many problems and accepts evidence level based on consensus [5][6].

The basis of impact assessment depends on the degree of relevant and matching inventory data, which further determines the normalisation factor and associated weighting factor for selected (or for all) impact assessment categories in relative of total environmental impacts.

3.7 Special requirements for system comparisons

Within the underlying LCA, the system of the excavation pit of the LVB will not be compared to other products and therefore, there are no special requirements to fulfil in this regard.

3.8 Critical review needs

No critical review is needed as of now but if the study is intended to be published by NGI, external critical review will be required.

3.9 Planning reporting of results

The results of the study will be delivered in terms of a written report, a presentation as well as the SimaPro Model.

4 Life Cycle Inventory Analysis

This section focuses on the Life Cycle Inventory (LCI) of this study. First, the processes for this study are identified (section 4.1) and briefly explained (chapter 4.2). This is continued in section 4.3, where the description which of these processes will be included in the LCA and how they are connected to each other is described. In the further sections, the collection of Data (section 4.4) and the assumptions made within the LCI (section 4.5.1) can be found. In the last chapters of the LCI, the unit processes as LCI results are described in section 4.6, before the theoretic description of the sensitivity and uncertainty analysis (chapter 4.7) is described.

4.1 Identifying processes for the LCI

The object of assessment in this report, the geotechnical work of the LVB in Oslo, consists of eight different steps:

- Site Investigation
- Soil Stabilisation
- Sheet Pile Wall
- Excavation of masses
- Anchoring
- Steel Core Piles
- Ground Floor Slab
- Earthworks

4.2 Explanation of System processes

The different system processes will be explained in this section as followed:

Site investigation: Within the first process of the set up the excavation pit, the area of the construction site was analysed. The objective is it to know what circumstances this specific site contains to conclude what actions have to be taken to secure the building. Therefore, the site was cleaned, samples of the soil were taken and analysed in a laboratory. Further actions contained, the determination of the bedrock depth, drilling and excavating small amounts of soil to also identify differences of the soil throughout the depth. Hence, in this process some excavator and drills were used in a small extent to clean the site and be able to determine the circumstances to deal with [11].

Soil stabilisation: The soil around Oslo is dominated by so called quick clay, which tends to flow and performs as a liquid when to much pressure is loaded on it. Therefore when you want to implement a construction site and also a building the soil has to be stabilised in the first place. Due to the fact, that also the equipment and machinery could be sufficient to overload the quick clay, this has to be done before the "normal" construction process can start. The stabilisation is done by implementing a cement mixture as columns into the ground. Therefore, a high speed drill is used to create a kind of column space in the ground, when going down. When the drill goes up again it is releases the cement mixture into the ground, where it forms columns of cement-soil. This process can be seen in figure 5 [17][11][16].

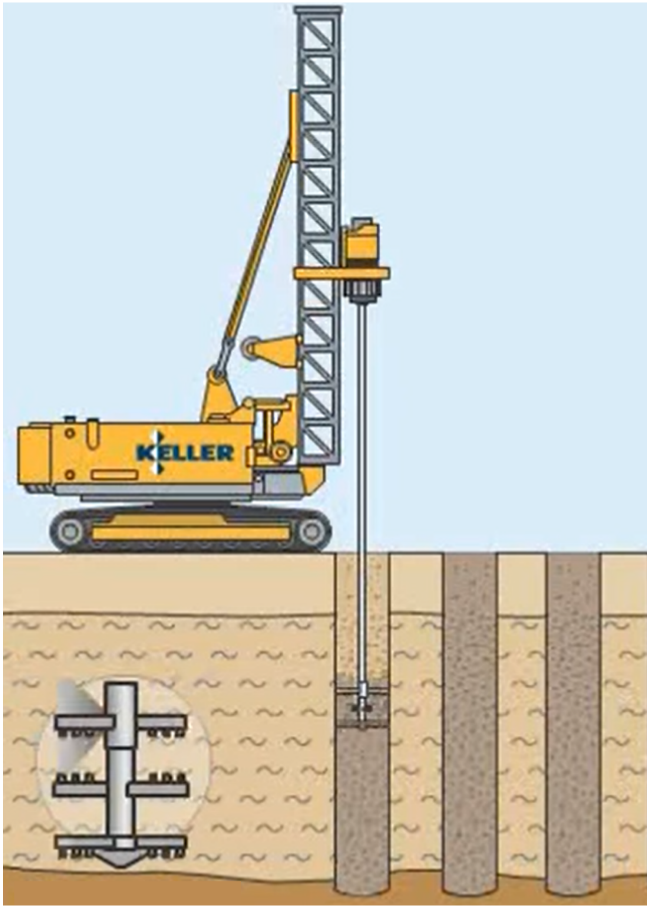


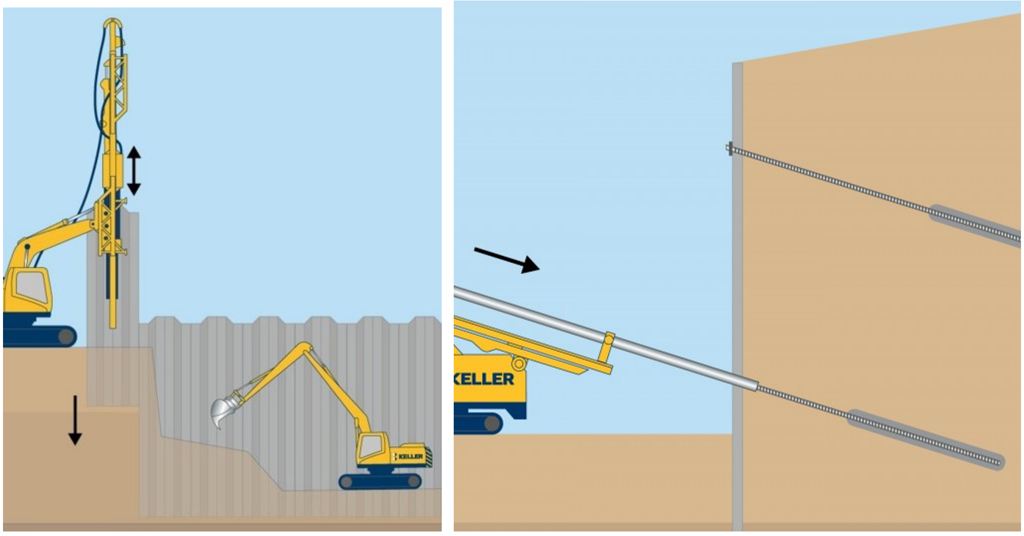
Figure 5: Soil stabilisation process [17]

These columns will safeguard the construction site and especially secures the quick clay from destabilizing when creating a building on top of it.

Sheet Pile Wall: The sheet pile wall is necessary to set boarders for the excavation pit and is safeguarding the excavated area from the masses around. The wall holds the masses next to the pit back from collapsing into it. The wall is, with the help of a vibratory hammer, being pushed into the ground step by step. This process is illustrated in figure 6a. The sheet pile wall will remain in the ground for the whole production and life time of the building [11][19].

Excavation of masses: The excavation process will create the pit for the building. Hence, the mixture of the implemented cement mixture and soil will be excavated by excavators and transported to landfill. Due to the contamination of concrete the soil is contaminated and can not be used for other processes. This step is being done after establishing of the sheet pile wall and simultaneously with the anchoring of the sheet pile wall. A picture of this process can be seen in figure 7 [11].

Anchoring: As mentioned in the paragraphs above, after establishing the sheet pile wall and while excavating the masses of the pit the sheet pile wall is anchored. This is illustrated in figure 6b. The purpose is it to ensure the stability of the sheet pile wall and safeguarding it of collapsing into the pit. This is necessary as there are high pressures from the soil behind the sheet pile walls on the wall itself. The process of anchoring is powered by drills to make space for inserting the wires and concrete [11][18].



(a) Establishment of Sheet Pile Wall [19]

(b) Anchoring of Sheet Pile Wall [18]

Figure 6: Establishment and Anchoring of Sheet Pile Wall

Figure 7: Simultaneous process of anchoring and excavating [11]

Steel Core Piles: The steel core piles are part of the foundation of the building and will help to secure the stabilisation of the building. The piles itself consists of a steel core, a steel casing and the space between is filled with concrete. This process is mainly supported by a pushing vibratory hammer. On the construction site of the LVB of around 17,000m^2 there are more than 1400 piles established as part of the foundation [11].

Figure 8: Establishment of Steel Core Piles [20]

Ground Floor Slab: The Ground floor slab consists of two layers. The first one is out of so called "Magerbetong" (low quality and more rough concrete) and enables the further construction on site; e.g. the carrying materials with trucks and other heavy machinery. The second layer is out of "normal" and more fine concrete, which will be the actual slab. The slab is set up in the full pit and creates the foundation of the building [11].

Figure 9: Construction site of the LVB with foundation, sheet pile walls and anchors [11]

Earthworks: Within the last process of the excavation pit the holes will be filled with soil again. Further, preparations as well as cleaning of the site are necessary to prepare the construction site for the further construction of the building [11].

4.3 Flow Chart of processes

The steps described in section 4.2 have different inputs and emissions. The detailed flow chart of the geotechnical works can be found in the figure below (10). The first process “Site investigation” as well as the last process "Earthworks" will be excluded in the analysis of this project due to lack of relevant documentation and data of the different tasks and steps. Further, it was recommended and requested by NGI to discard these two processes as the it is assumed by NGI that the impact is neglectable [11].

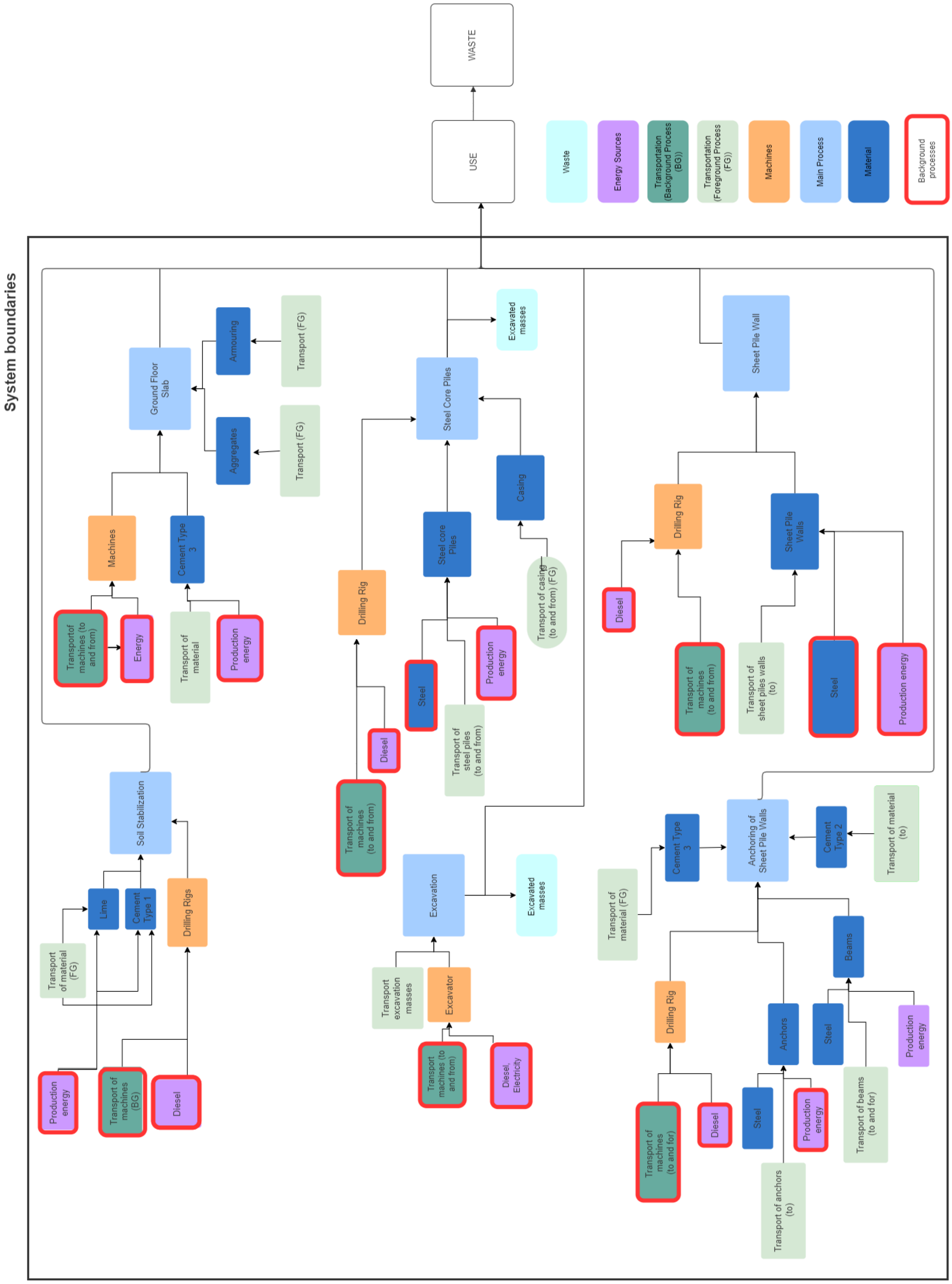


Figure 10: Flow Chart for all analysed processes

4.4 Data collection

For the LCI, different types of data sources were used. Due to the high specificity, the priority was to acquire first-hand data from NGI and the contractors. Where this was not possible, NGI themselves made assumptions under a “best guess” approach from previous relevant projects and experiences. For other data gaps, the student group made assumptions based on relevant data from other data, projects, and sources. This data is specific to the project and can be classified as primary data, while most of the data for the use of material were taken from Ecoinvent Databases and is therefore secondary data. The sources of the data can be found in the table in the Appendix A.1 (A.1.1 and A.1.2).

Table 2: Data Specificity for different processes - Summary (detailed table in the Appendix A.1.1)

Process	Representativeness				
	Very High	High	Medium	Low	Very Low
Soil Stabilization		X			
Excavation of masses			X		
Sheet Pile Wall			X		
Steel Core Piles			X		
Anchoring			X		
Ground Floor Slab				X	

The different data sources shown in Table 1 have different levels of specificity, more details of specificity for each subprocess can be found in Appendix A.1.1. In the first place, the data provided by NGI based on contractor and suppliers’ data is very high specificity, as it comes directly from measurements of the specific processes. This is the case for some of the transport distances and some of the truck loads, which data was directly by the transportation companies [11]. In a lower level of specificity (high) is the data provided by NGI derived from measurements via calculations and modelling. This is the case for data on the masses and quantities derived by calculations on density and geometry of the different materials. With medium specificity is the data coming from LCI databases [21] that has been modified with specific data from measurements, as in the modelling of some transportation processes where emissions were known. In the low specificity level, it is data from literature and generic database processes. Lastly, assumptions from NGI and students based on their own judgement are on the low specificity data.

4.5 System Modelling Per Life Cycle Stage

4.5.1 Assumptions for LCI

Below, the details of the system modelling, the data collected and treatment can be found. Further, the major assumptions are presented for each unit process.

Assumptions applied to all processes: For Machine transport it has been assumed to be done for all individual processes as a conservative assumption and consequently no machines were used from other processes. The transport distance for machines has been assumed to be the same for all machinery. As "Seabrokers" is the delivering company of the machine, the distance to their main office has been calculated. The weight of the machines are determined as the averages on machine information of "seabrokers" (e.g. Excavator weight assumed 36.5t [26]. Furthermore, it was assumed, that several machines can be transported on one truck (assumption of highly efficient transport capacity for all machinery transport). Since the transportation company responsible for the lime and cement transport (Sørum transport) states to use states EURO6 standards [27] it was introduced standard since 2014, it will be assumed to be EURO6 for all transportation companies. Furthermore, it is assumed that materials of the same kind are always transported from the same supplier and transportation processes are always done in the most efficient way (fully loaded with the minimum amount of trucks possible).

Soil stabilisation: In this process, a multicement mix of 50% cement and 50% multicement is applied for the soil stabilisation columns[22] for the actual performed process at the LVB contruction project. The best approximation of this is Cement, blast furnace slag 31-50% and 31-50% other alternative constituents was chosen (see detailed description in subsubsection 6.4.1. The machine operation was calculated based on given machine hours and Diesel density from literature [23]. As the machinery was assumed to be excavators with tooling and operating parts that can be changed to function as a drilling rig, the weight of machines (36.5t) was determined as average value from "Seabrokers" machinery [26].

Sheet Pile Walls: To calculate the weight of the sheet pile walls data from literature were taken [28].

Excavation of masses: The excavation of masses includes the transport processes by truck and ship to different landfill locations. The transportation by ship of the excavated masses is carried out by a new technology hybrid ship, which is why the emissions of Diesel CO_2 and NO_X were adjusted according to the information provided [24]. The hybrid ship has 20% less Diesel consumption as well as CO_2 emissions. Furthermore, the NO_X emissions are reduced by 85%. Furthermore, an empty return of the ship is assumed and a load factor of 80%, since the ship is not exclusively transporting masses from the excavation pit. The volume of total excavated masses was calculated with the density of wet marine clay [29].

Anchoring: For the material transport of the anchoring parts, the same transport distance as in the process of "sheet pile walls" was assumed for the steel parts (distance to main office of Seabrokers), whereas the transport distance for cement was assumed to be the same as in soil stabilisation (transport distance for cement given by NGI). Furthermore, it was assumed that the steel is unalloyed for all anchoring parts [30; 31], whereas the diameters of the hollow steel tubes were averaged. Portland cement for the filling of anchors was based on EPD information [32].

Steel core piles: For the steel core piles, the transportation distance of the materials from the main office "Seabrokers" was assumed. The process was modelled with EPD data of Norwegian Steel Core Piles. According to [35] the standard steel grades are S355J2/S355J0 with dimensions of Ø 50mm-200mm. Based on that, average values of Ø 125mm, was determined for the piles. The design of the casings was made based on literature [33]. The casing diameter was determined as 0.3m, whereas the thickness of the casings was specified to be 0.008m. The volume between the piles and the casing is filled with concrete, which is mixed at the site. Therefore, transportation of the dry concrete was considered in SimaPro. The total mass of dry concrete was calculated with density values from [38], whereas the transport distances were assumed to be the same as for the soil stabilisation (data on transport distance for lime and cement) and sheet pile walls (steel). Additionally, transport of machines for the establishment of the steel core piles was assumed to be the same as for the soil stabilisation. It is assumed that excavators that the tooling/operating parts on excavators can be changed to function as a drilling rig. Furthermore, the mass of waste (drilling sludge) was calculated with the density of wet marine clay [29].

Ground-floor slab: For the implementation of the ground-floor slab, the whole process needed to be created based on assumptions. In consultation with NGI, it was agreed that a slab is consisting of two different concrete layers. Additionally, it was stated that no other materials like steel grids within the concrete slab can be considered in this study [11]. The first layer consists of lean concrete (concrete with lower quality, which is only used for subsoil stabilization and thus for construction works with heavy machinery. For this layer, a thickness of 0.1m was determined. On top of this, another concrete layer with a thickness of 0.2m is placed, which has a higher material quality. Furthermore, the use of machines (machine operation), the transport of machines for the establishment of the ground floor slab is not modeled. Furthermore, for the ground floor slab, an area corresponding to the given floor area of the life science building was assumed. For the calculation of the total mass for lean concrete and concrete, general densities from external sources were used [39]. The distance of material transport for lean concrete and concrete was assumed to be the same as for other materials, where more information was available (from the main office of Seabrokers).

Other data information: The data was validated in cooperation with NGI, this counts for the data provided by NGI themselves and especially the assumptions made by the company. Further, most of the student assumptions were cross checked with NGI. Scaling of data to the FU was not necessary because the data was already delivered in terms of the defined reference flow of one excavation pit.

4.6 Unit processes and LCI result

For modelling the relevant processes in SimaPro it was needed to create unit processes for each modelled process as well as for the final product – the excavation pit. This ends up in the following modelled processes, the details of the data of the processes can be found in the Appendix A.1.2:

- Soil stabilisation (Appendix A.1.2 table 7)
- Sheet Pile Walls (Appendix A.1.2 table 8)
- Excavation of masses (Appendix A.1.2 table 9)
- Anchoring (Appendix A.1.2 table 10)
- Steel core piles (Appendix A.1.2 table 11)
- Ground floor slab (Appendix A.1.2 table 12)
- Final Pit (Appendix A.1.2 table 13)

The used data representativeness as well as the data sources can be found in the Appendix A.1.1 table 6). Further, a discussion about how each process was modelled as well as the representativeness of the chosen unit processes can be found within the discussion (chapter 6.4.1).

4.7 Basis for Sensitivity and Uncertainty Analyses

In the study, certain assumptions were made (more details in chapter 4.5.1) and it is therefore of great relevance to perform a sensitivity analysis to determine the influence of our assumptions made on the results of the Life Cycle Assessment study. Subsequently, uncertainty and variability analyses are performed to determine the accuracy of the model output, more specific the Life Cycles Impact Assessment results, which will be described in the next section (chapter 5).

4.7.1 Sensitivity analysis

Perturbation analysis: To perform a sensitivity analysis on perturbations, normalised sensitivity coefficients ($X_{IS,k}$) are calculated to determine which of the parameters are sensitive and therefore influence the results the most. To do so, the following equation (1) were used:

$$X_{IS,k} = \frac{\frac{\Delta_{IS}}{IS}}{\frac{\Delta_{a_k}}{a_k}} \tag{1}$$

- k Parameter
- a_k Default value of parameter k
- Δ_{a_k} Pertubation of parameter ak
- IS Calculated impact score for parameter value ak
- Δ_{IS} Change of the impact score that results from the perturbation of parameter ak
- $X_{IS,k}$ Normalised sensitivity coefficient of impact score (IS) for perturbance of a parameter k

All input parameters from each unit process has been perturbed by 10%. The normalised sensitivity coefficient(NSC) for all input parameters and each impact category has been calculated. The parameter has been identified as sensitive if the absolute average value across all impact categories is greater than 0.3 or the individual NSC is greater than 0.5 [6].

Scenario analysis: To analyze the uncertainty coming from the input parameters in each unit process created in SimaPro, a scenario analysis has been performed.

In this, the contribution of each input has been mapped out by analyzing each unit process separately and the respective model parameters are laid out. After identifying the model parameters, the alternative scenarios has been chosen on the basis of best closely representativeness in relative to the original model parameter. Their relative percentage change has been calculated with equation 2, the alternative scenarios chosen have been documented and the threshold of 15% on a single impact category or 10% on the average of absolute values has been determined to filter the input parameters with most impacts. After identifying the model parameter, the threshold of 100% relative change has been set to see the potential change it might have on the results.

$$\%_{relativechange} = \frac{IS_{scenario} - IS_{base}}{IS_{base}} * 100\% \tag{2}$$

- *ISscenario*: Impact score after implementing the scenario
- *ISbase*: Impact score from the baseline results

4.7.2 Quantitative uncertainty analysis

Representativeness Analysis: In representativeness analysis, the quantitative scale of data quality has been laid out, which can be found in appendix A.1.1 table 6. And the in-depth discussion of each input parameter for every unit process has been done from the geographical, technological and temporal scope in the section 6.4.1.

Key data analysis: In the key data analysis, data from perturbation sensitivity analysis (Appendix: Table 22) has been plot against the quantitative value of data representativeness (Appendix A.1.1 table 6). Hence, parameters with high lack of data and high sensitivity are determined as key data. Also parameters with high representativeness and high sensitivity are accounted as key data (low priority). These determined key data, represent the identification of parameters, for which more precise data are needed, since they have significant impact(s) on the results.

5 Life Cycle Impact Assessment

This chapter focuses on the description of the Life Cycle Impact Assessment (LCIA) results. For the LCIA, the software SimaPro and the method "ReCiPe 2016 Midpoint (H) V1.05 / World (2010)" has been used. This specific method implies the use of a hierarchic perspective, which has been chosen due to the balance between long and short term time perspective. The LCIA results will be first described as Midpoint (section 5.1) and than as Endpoint (section 5.2) results.

5.1 Midpoint results

The midpoint result will be first described as characterized (section 5.1.1) then as normalized (section 5.1.2) and finally as weighted (section 5.1.3) values.

5.1.1 Characterization of Midpoint results

The characterized values for the midpoint impact categories have been calculated using the method ReCiPe 2016 Midpoint (H) V1.05 / World (2010) and can be seen in the table 15 (in Appendix A.2). In the following section the characterized results of the study will be described. First the process contribution will be presented before the substance contribution will be analysed.

Process contribution analysis: The main goal of this LCA study is to determine which of the involved processes in the establishment of an excavation pit had the biggest environmental impact. Hence, a process contribution analysis has been conducted and the results can be found in figure 11.

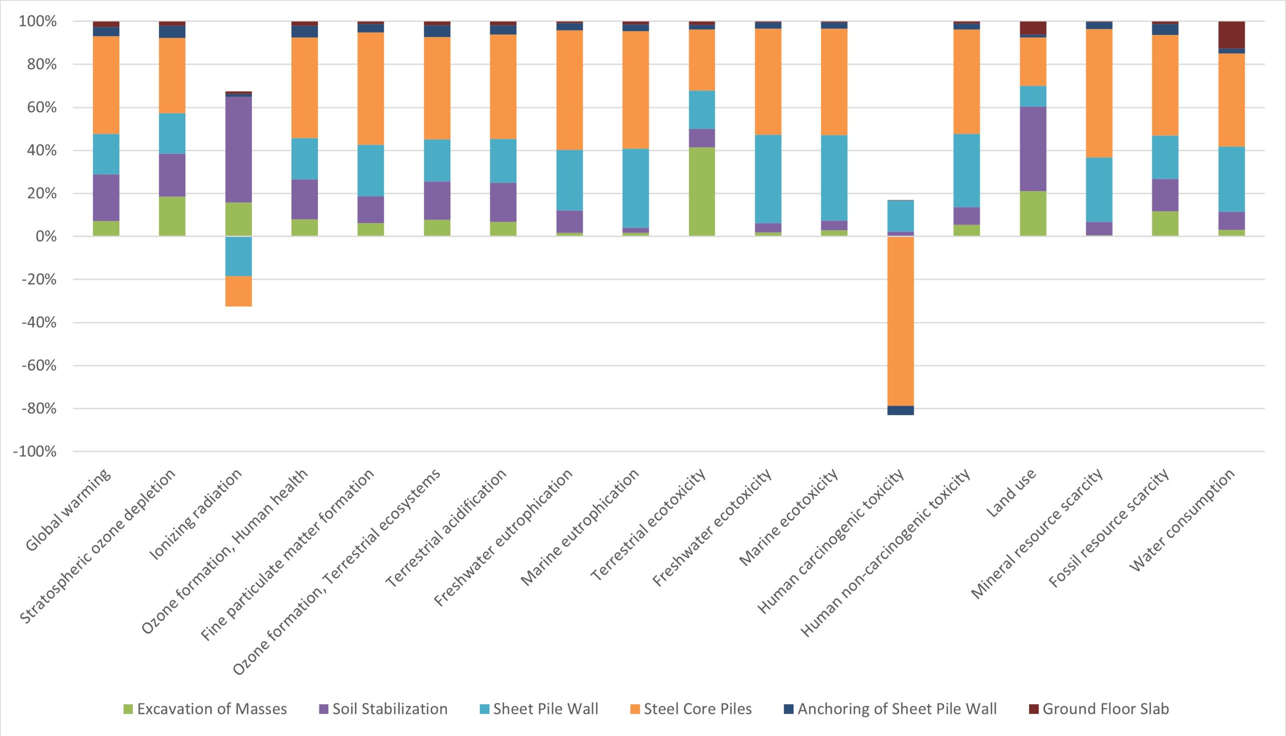


Figure 11: Characterized values for the midpoint impact categories.

It shows that the main driver of impact across almost all midpoint categories is the steel core piles process, contributing more than 50% to marine fine particle matter formation, freshwater eutrophication, marine eutrophication and mineral resource scarcity; and being the process that contributed the most to all impact categories except for land use (22% after soil stabilization), terrestrial ecotoxicity (28% after excavation of masses), ionizing radiation and human non-carcinogenic toxicity (where it has a positive impact). Then, the second most contributing process is sheet pile wall, which accounts for between 20% and 40% in various impact categories: fine particulate matter formation, terrestrial acidification, freshwater eutrophication, marine eutrophication, freshwater ecotoxicity, marine ecotoxicity, human non-carcinogenic toxicity, mineral resource scarcity, fossil resource scarcity and water consumption. Further, the sheet pile wall process has also the biggest contribution impact (14%) to human carcinogenic toxicity and a negative contribution in ionizing radiation (-18%). The third most contributing process is soil stabilization, which has the biggest contribution in ionizing radiation and land use, and contributes between 15% and 25% to global warming, stratospheric ozone depletion, ozone formation (both to human health and to terrestrial ecosystems), terrestrial acidification and fossil resource scarcity.

On the other hand, the impacts with a smaller contribution are excavation of masses, anchoring and ground floor slab. Excavation of masses contributes the most, as mentioned before, to terrestrial ecotoxicity with a weight of 41%. It is also significant its contributions to stratospheric ozone depletion (18%), ionic radiation (16%), land use (21%) and fossil resource scarcity (12%), and it is small to very small (less than 8%) to the rest of midpoint impact categories. Anchoring is the next process in terms of contribution, with values lower than 6% in all impact categories. Last but not least, ground floor slab us the process with the smallest impacts, only contributing more than 3% in land use (6%) and which in most categories its contribution is around 1%.

Overall, it can be said that there is a clear hierarchy in terms of which processes are more impactful and that is: steel core piles, sheet pile wall, soil stabilization, excavation of masses, anchoring of sheet pile wall and ground floor slab. How significant is the difference between each process in total terms will be discussed in section 6.

Substance contribution analysis. The contribution analysis has also been performed at the level of elementary flows to give additional insights into the sources of environmental consequences from the excavation pit's establishment, identifying the chemicals that create the greatest environmental burden. The detailed results can be accessed in Appendix A.2.2.

Global warming impacts are mainly driven by emissions of carbon dioxide (CO_2), which contributes to 90% of the total impacts. The biggest contribution processes to CO_2 emissions are steel core piles (44%) and soil stabilization (22%). The methane (CH_4) emissions cause another 8% of global warming total impact, being steel core piles the biggest contributor (62%). Potential impacts of photochemical ozone formation on human health are mainly due to emissions of nitrogen oxides (NO_x), which account for 87% of the total impact. Again, steel core piles (44%) and soil stabilization (20%) are the main contributors.

Sulphur dioxide (SO_2) (61%) and Nitrogen oxides (NO_x) (34%) are the substances that dominate the acidificaton impacts in terrestrial ecosystems. Steel core piles (50%) and sheet pile wall (22%) contribute more to SO_2 emissions, while steel core piles (45%) and soil stabilization (20%) account the most for NO_x emissions. Toxic impacts in freshwater ecosystems are dominated by emissions of metals: cooper (46%), zinc (22%) and vanadium (26%). Once more, sheet pile wall (51%) and steel core piles (41%) contribute more to these emissions. The results for marine ecotoxicity are very similar: cooper (41%), vanadium (28%) and zinc (21%) are the substances that lead the impact and sheet pile wall and steel core piles are the most impactful processes in this regard. For human carcenogenic toxicity, a negative impact is found due to the negative contribution Steel core piles and Anchoring have to Chromium emissions. Regarding non human carcenogenic toxicity, zinc (51%) and arsenic (12%) are the substances that most contribute.

For mineral resource scarcity, iron is the leading substance in terms of impact contribution, causing 66% of the impact. Then, nickel and molybdenum follows with 12% impact contribution each. The process that accounts for the most impact in this category is steel core piles, with 60% and due to the big quantity of steel that it requires. For this same reason, sheet pile wall is the next process, with 30%. Regarding fossil resource scarcity, the substances that have the biggest impact are coal (51%), oil (37%) and gas (10%) and steel core piles (47), sheet pile wall (20%) and soil stabilization (15%) the processes that use most of these substances.

5.1.2 Normalized midpoint results

The normalization of the midpoint results has been done with external normalization where the common unit is person equivalents (pe) with the reference of a the annual impact of an average person in the European Union (EU27) in 2010. The purpose of conducting this normalization is to disclose if the results are in an order of magnitude adequate and reasonable to the defined reference flow. A table (table 15) with the values can be found in Appendix A.2. The corresponding graph for the total values of all processes can be found in figure 12 and will be described below.

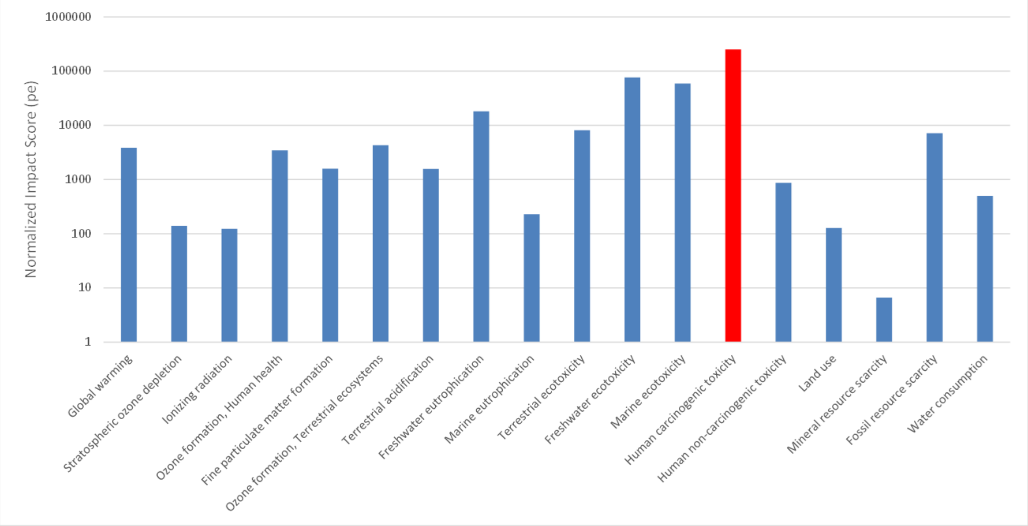


Figure 12: Normalised impacts (log10-scale) in person equivalents (pe) the total of the excavation pit. **The red column means that for Human carcinogenic toxicity the result is negative**.

The biggest normalized impact is in freshwater ecotoxicity, where the impact corresponds to approximately 80,000 times the total annual average impact of an European citizen in 2010. The second biggest normalized impact score is in the category of Marine ecotoxicity, which has a pe score of 60,000.

For climate change, the impact corresponds to approximately 4,000 of the total annual average impacts of an average EU27 citizen in the year 2010. In the same order of magnitude, it is the impact in ozone formation (both human health and in terrestrial ecosystems). In the case of stratospheric ozone depletion, the impact corresponds to around 100 of the total annual average impacts of an European citizen in 2010. In the same order of magnitude is the case of ionizing radiation and land use, and the double for marine eutrophication which is 228 times bigger. It is also relevant to mention the big normalized negative impact in the category of human carcinogenic toxicity, which is the absolute biggest impact and which, as mentioned before in section 5.1.1, corresponds to the steel type chosen for steel core piles and Sheet pile wall.

Overall, it can be said that the results are in an order of magnitude that is reasonable with the magnitude of the analysed reference flow of one excavation pit.

5.1.3 Weighted normalized Midpoint results

In the following, the weighted midpoint results have been explained. It should be noted that except for terrestrial ecosystems, steel core piles always have the highest contribution in environmental impact compared to the other processes studied. For the protection area human health, the impact on global warming, fine particular formation and human carcinogenic toxicity is visible in all processes (Figure 22). The contribution of steel core piles is the highest. The impact on human carcinogenic is negative, since 80% recycled steel is used for steel core piles, whereas in the process of the sheet pile walls, human carcinogenic toxicity has a positive impact) are made of 3 different, non-recycled steel grades.

For terrestrial ecosystems, the excavation pit system procsses have been found to contribute mainly to terrestrial ecotoxicity (Figure 23). The largest contributor is the process of excavation of masses. The impact on land use across all processes was also found, but with a small contribution compared to the impact on terrestrial ecotoxicity.

In the weighted mid-point results, the steel core piles process was also detected as the highest contributor Figure 24. The impact category of freshwater eutrophication across all processes is dominant. Furthermore, all processes contribute to freshwater ecotoxicity, but to a lesser extent than eutrophication.

In the context of marine ecosystems, the processes studied are mainly responsible for impact on marine eutrophication and marine ecotoxicity Figure 25. Again, the steel core piles are significantly the main contributor compared to the other processes. the steel core piles are the second highest contributor, whereas the ground floor slab contributes the least to the impact on marine ecosystems.

In terms of resource scarcity, the steel core piles are also dominant in their impact on fossil and resource scarcity Figure 26. All processes have a significant impact on fossil resource scarcity. In the processes soil stabilization, sheet pile walls, and anchoring, impacts on mineral resource scarcity are visible, but to a much lesser extent.

5.2 Endpoint impact results

The Endpoint results of the impact assessment will be discussed within the following chapter. First, the characterized results (section 5.2.1) will be presented before the normalized endpoint results (section 5.2.2) will be mentioned. To conclude this section the weighted endpoint results (section 5.2.3) will be described.

5.2.1 Characterization of Endpoint results

The Endpoint impact categories are representing the areas of protection. These are Human health, Ecosystems and Resources and can be found in table 3 for the six processes of this study. It is distinct, that the Steel Core Piles contributing the most to all the impact categories, which can be seen in the table in bold font.

Table 3: Characterized endpoint results for all impact categories and all six processes; The maximum value per impact category is highlighted in bold text

			Processes					
Impact category	Unit	Total	Excavation of Masses	Soil Stabilization	Sheet Pile Wall	Steel Core Piles	Anchoring	Ground Floor Slab
Human health	DALY	51.429875	4.018863	10.13911	15.30421	**18.97894**	1.886278	1.102476
Ecosystems	species.yr	0.1277337	0.010161	0.026733	0.024561	**0.057838**	0.005281	0.00316
Resources	USD2013	1917237.2	350165.3	355866.3	366109.2	**704116.1**	111967	29013.26

The contribution of the six processes to the three categories can be found in the appendix A.2, figure 27. There it is straight forward, that for all three endpoint impact categories (Human health, Ecosystems and Resources) the steel core pile process has the highest impact. With around 37% for Human health and Resources and 45% for the impact category of Ecosystems. The establishment of the sheet pile wall has impacts Human health with around 30% and the other two impact categories with about 19%. Next to that, the soil stabilisation process is accounting for around 20% for all the three areas of protection. The impact category of resources is coming from 18% of the Excavation of masses, whereas the other contributions of this process have a rather smaller impact (about 8%) to Human health and Ecosystems. The missing two processes, anchoring and Ground floor slab having in general a minor contribution to the endpoint impact results. Where Anchoring is accounting for 4% for Human Health and Ecosystems, it is responsible for 6% of the total impact on resources. According to the Endpoint impact results the ground floor slab has only an impact of 2% for all the areas of protection.

In appendix A.2, table 19 all single values referring to the three endpoint impact categories can be found. There it can be seen, that the process contribution described above is reasonable and align with the characterized values, as the negative impact categories are being balanced with the positive values for the three areas of protection in the endpoint.

5.2.2 Normalization of Endpoint results

Within this LCA study the normalization of the endpoint results has also been performed. The values for the three categories as well as the six processes, can be found in the appendix A.2, table 20. Two graphs of the normalized results one with all three impact categories and one just for ecosystems and resources can also be found in the same Appendix section in figure 28 and 29 respectively. It is distinct that the allocation is similar to the one of the characterized endpoint results and is in the same order of magnitude. This consequently strengthens the claims of the previous sub-chapter and the results stated there.

5.2.3 Weighted normalized Endpoint results

Weighting of LCIA results are done, to compare and add impacts from different impact categories, for example to conclude on a total impact of a process or a product. This can be done with various perspectives (Individualist, Egalitarian, Hierachist) which are different in terms of the time-horizon, the managability (whether technology or policy driven) as well as the required level of evidence [5][6]. Due to its balanced time-horizon the hierachic perspective was chosen and weighted accordingly. These weighting factors for the different areas of protection can be seen in Table 4[5].

Table 4: Applied weighting factors of normalized endpoint result [5]

Area of protection	Endpoint weighting factors
Human health	300
Ecosystems	400
Resources	300

The weighted results of the LCIA can be found in appendix A.2.7, table 21 and seen as graphs in the figures 13 (weighted results per process) and in the appendix A.2, figure 30 (weighted results per impact category). In figure 13 it can be seen that the steel core piles are the most impactful category with around 260,600 weighted Person equivalent (wPe) and a contribution of 37% of the total impact. Followed by the sheet pile wall with nearly 202,000 wPe (29%) and the process of soil stabilization with circa 137,900 wPe (20%). With quite a big difference are than coming the processes of Excavation of masses with around 56,800 wPe (8%), Anchoring with nearly 26,200 wPe (4%) and the ground floor slab with around 15,000 wPe (2%).

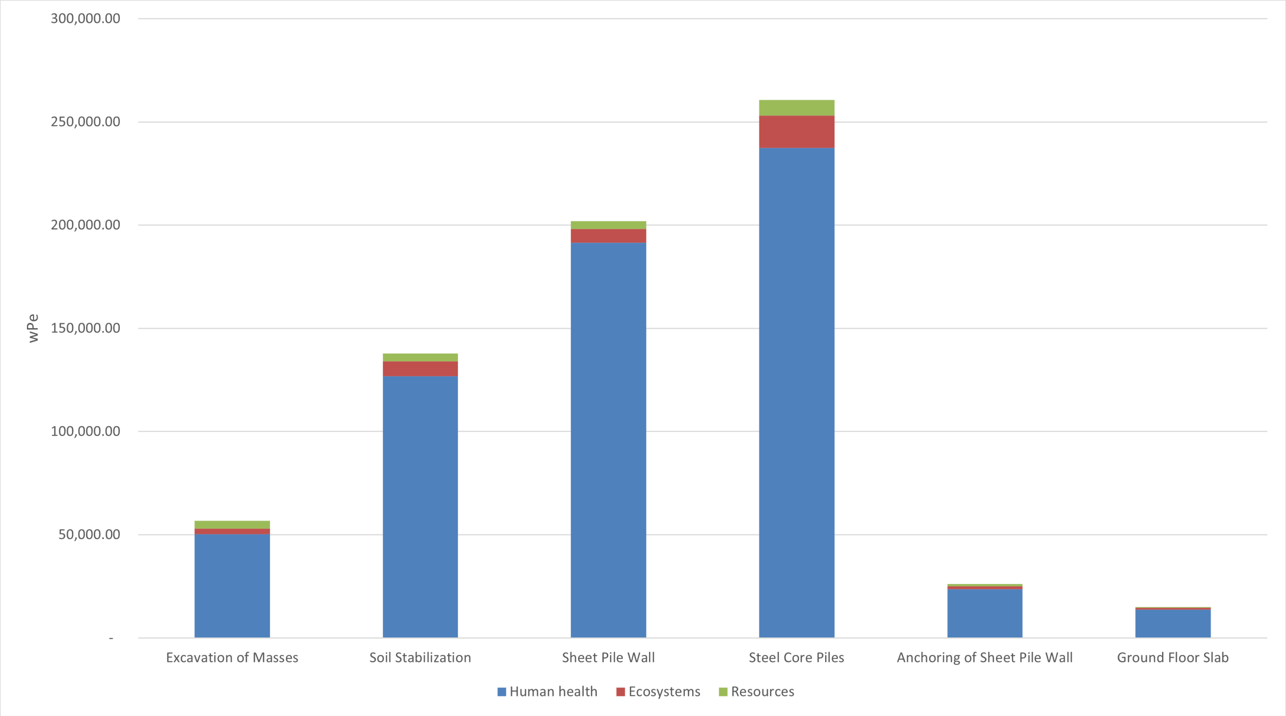


Figure 13: Process contribution of weighted external normalized endpoint results by process

Regarding the weighted results in terms of the three endpoint impact categories it is distinct that human health is most impacted by the excavation pit of the LVB, with a total impact of slightly more than 643,000 wPe, which counts for 92.1% of the total impact. The Ecosystem is impacted by 34,500 wPe (3.8%) of total impact and the resources are following with 20,500 wPe and a contribution of 2.9%. This results in a total impact of the excavation pit of 698.460 wPe.

6 Interpretation and Discussion of results and uncertainties

In this section the results, presented in the previous section will be interpreted and critically discussed. From section 5 it seemed distinct that the process of Steel Core Piles are the most impactful driver for the set up of the excavation pit at the LVB. Further from the LCIA information it seems that the following order in terms of impact is resulting (from 1 with the highest impact to 6 with the least impactful process):

1. Steel Core Piles
2. Sheet Pile Wall
3. Soil Stabilisation
4. Excavation of masses
5. Anchoring
6. Ground Floor Slab

Therefore, all the weighted results were divided from each other to derive to a factor matrix. There, it can be seen with which number the total weighted impact of a process need to multiply with to end up with the impact of another process. This matrix can be found in the following table (5).

Table 5: Factors of difference for and from each process to each other, calculated values from total weighted results per process; values highlighted in bold are in descending order from the list above and figure 13

	Excavation of Masses	Soil Stabilization	Sheet Pile Wall	Steel Core Piles	Anchoring	Ground Floor Slab
Excavation of Masses	1	0.411761322	0.28103318	0.217852004	**2.16491657**	3.795785714
Soil Stabilization	**2.428591385**	1	0.68251475	0.529073499	5.25769773	9.218412485
Sheet Pile Wall	3.558298739	**1.465169794**	1	0.77518251	7.703419899	13.50653952
Steel Core Piles	4.590272216	1.890096557	**1.29001879**	1	9.93755638	17.4236897
Anchoring	0.461911565	0.190197317	0.12981247	0.10062836	1	**1.753317318**
Ground Floor Slab	0.263450067	0.108478548	0.07403821	0.057393125	0.570347415	1

Due to different sources of data, assumptions and unit processes and in general uncertainties this can just be framed as a intermediate result. Therefore, a sensitivity and uncertainty analysis has been performed. This can be seen within the next sub chapters, where first a sensitivity check in section 6.1 is performed. This is followed in section 6.2 by the interpretation of the weighted midpoint in combination with the sensitivity analysis and the impact method analysis in section 6.3. Finally, a qualitative uncertainity check is performed (section 6.4).

6.1 Sensitivity check

Within the following chapter a perturbation analysis (section 6.1.1) as well as a scenario analysis (chapter 6.1.2) is conducted.

6.1.1 Perturbation analysis

To see the potential influence of the input chosen in the unit processes on the final results, the perturbation analysis has been performed. The basis of the perturbation analysis has been described in section 4.7.1. The individual NSC coefficients for individual impact category and for each input parameter of each unit process can be found in appendix Table 22.

On the basis of the chosen threshold (4.7.1), three sensitive parameters have been identified, namely :

- Cement from the Soil Stabilization process
- Steel from Sheet Pile Wall process
- Steel from Steel Core Piles process

The input parameter “Material Steel" in the unit process "Steel Core Piles" has the most dominant influence on human carcinogenic toxicity, ionizing radiation, mineral resource scarcity, freshwater eutrophication and marine eutrophication. The most sensitive impact category to perturbation of the amount of steel is hereby “human carcinogenic toxicity” with a single score of NSC = 1.2, whereas the least sensitive impact category is “marine eutrophication” with a NSC of 0.53. In the unit process ”Sheet Pile Walls” the input parameter "Material Steel" has dominant influence on the impact category “ionizing radiation”. The normalized sensitivity coefficients are also quite high for freshwater ecotoxicity, marine ecotoxicity, marine eutrophication and human non-carcinogenic toxicitiy. The parameter “Cement” in the unit process “Soil Stabilisation” is also considered as sensitive, as the material has dominant influence on the impact category “Ionizing radiation”.

The observed normalized sensitivity coefficients (NSC) values for identified sensitive parameters for each impact category have been shown in Figure 14.

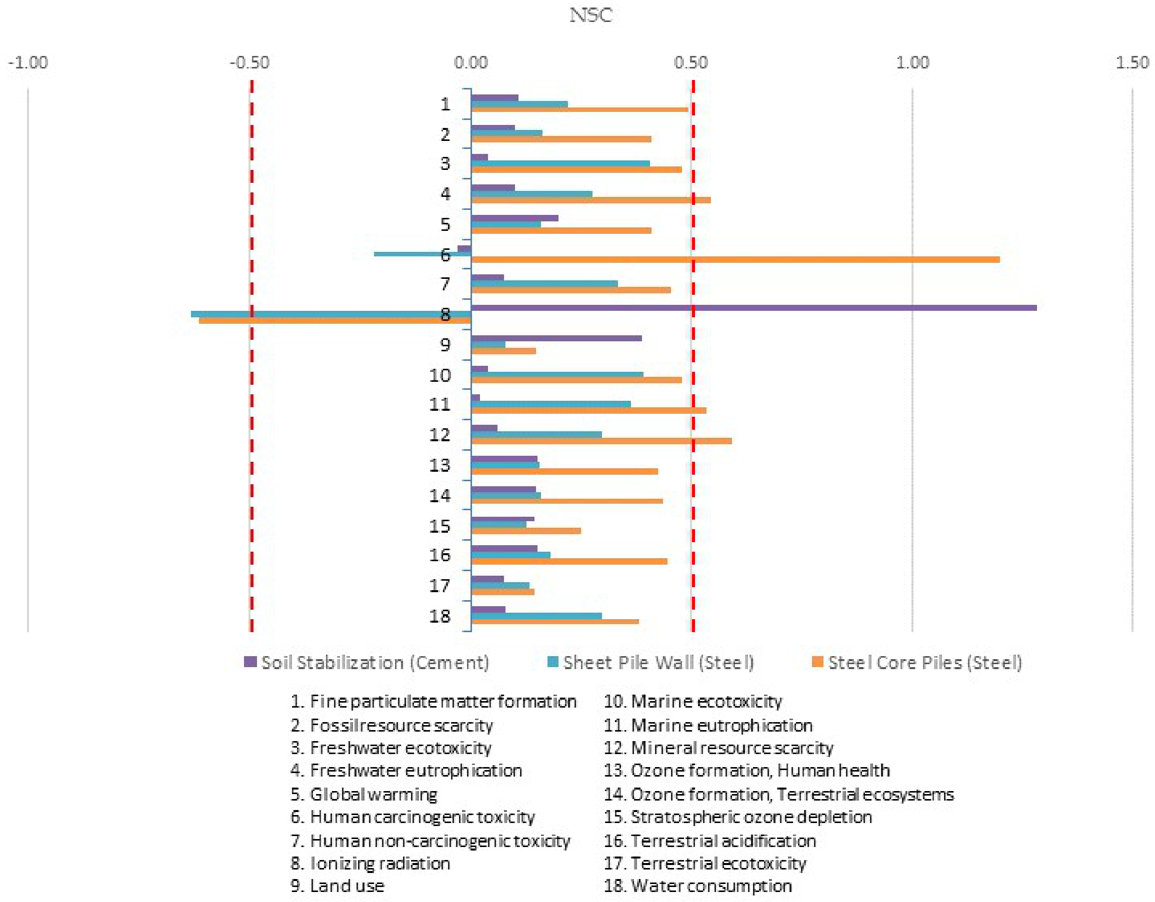


Figure 14: Normalized sensitivity coefficient (NSC) on all impact categories of the 3 parameters identified to be sensitive

So, it is imperative to consider the data much carefully for identified sensitive parameters, as they are playing an influential role in the conclusions drawn from the study. The assumptions made for these input parameters have been laid out in 4.5.1. Also, the associated decisions made while modelling them have been mentioned in 6.4.1.

6.1.2 Scenario analysis

To explain the uncertainty coming from the input parameters of each unit process the scenario analysis has been performed. The basis of the scenario analysis has been described in section 4.7.1. The threshold chosen is 15% on a single impact category or 10% on the average of absolute values to filter out the most impactful inputs (Appendix: Table 23).

To put in reference, how much each of these input parameters are contributing in each impact category, the following chart has been made:

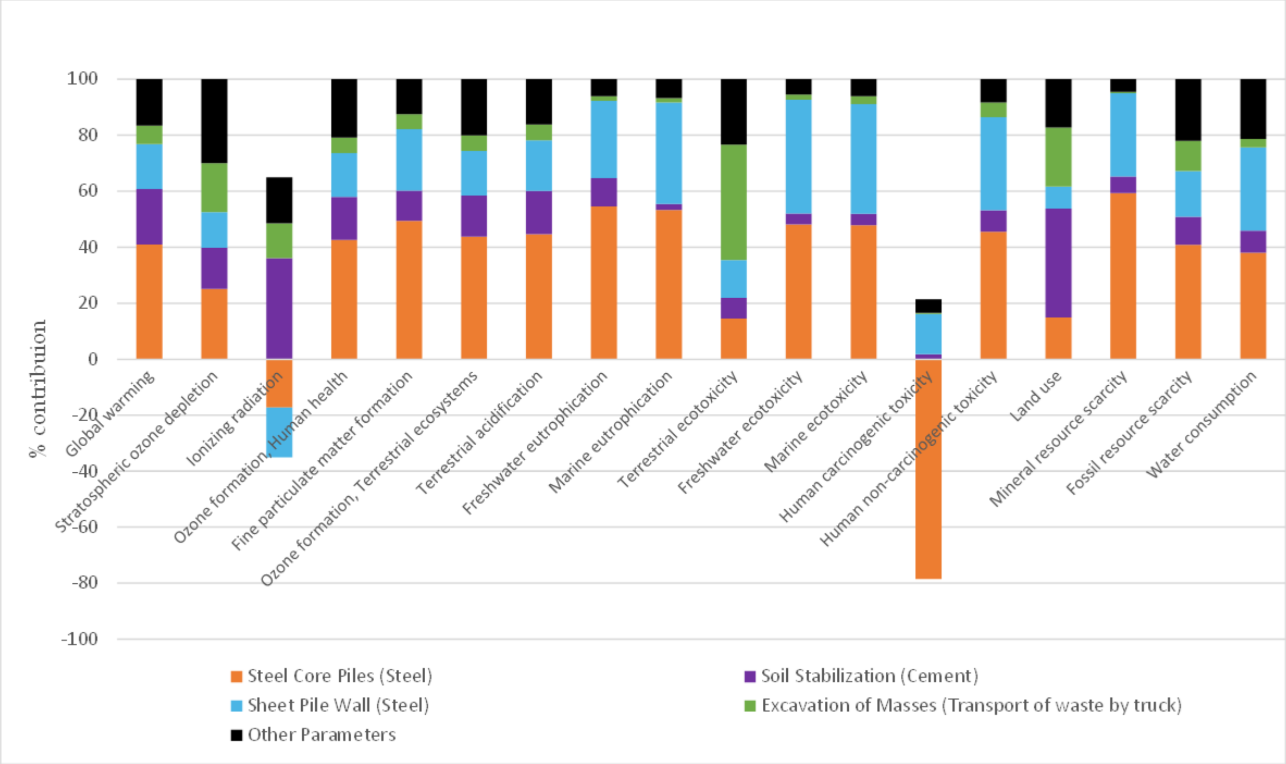


Figure 15: Normalised sensitivity coefficients of the three identified sensitive parameters for each midpoint impact category

To relate the sensitivity of alternative scenarios chosen for each model parameter, the threshold of 100% on percentage relative change has been assigned. The identified model parameters and results are discussed below:

Steel Core Piles: Model Parameter: Steel, unalloyed RER| steel production, converter, unalloyed | Conseq, U

- Scenario 1: Steel, low-alloyed, hot rolled RER| production | Conseq, U

  This alternative has been chosen because the steel grade used in Steel Core Piles is hot rolled as described in the Environmental Product Declaration (EPD) provided by NGI and low alloyed is the closest to the unalloyed in SimaPro.

- Scenario 2: Steel hot rolled coil/EU

  This alternative has been chosen because the steel grade used in Steel Core Piles is hot rolled and the geographical representativeness is appropriate.

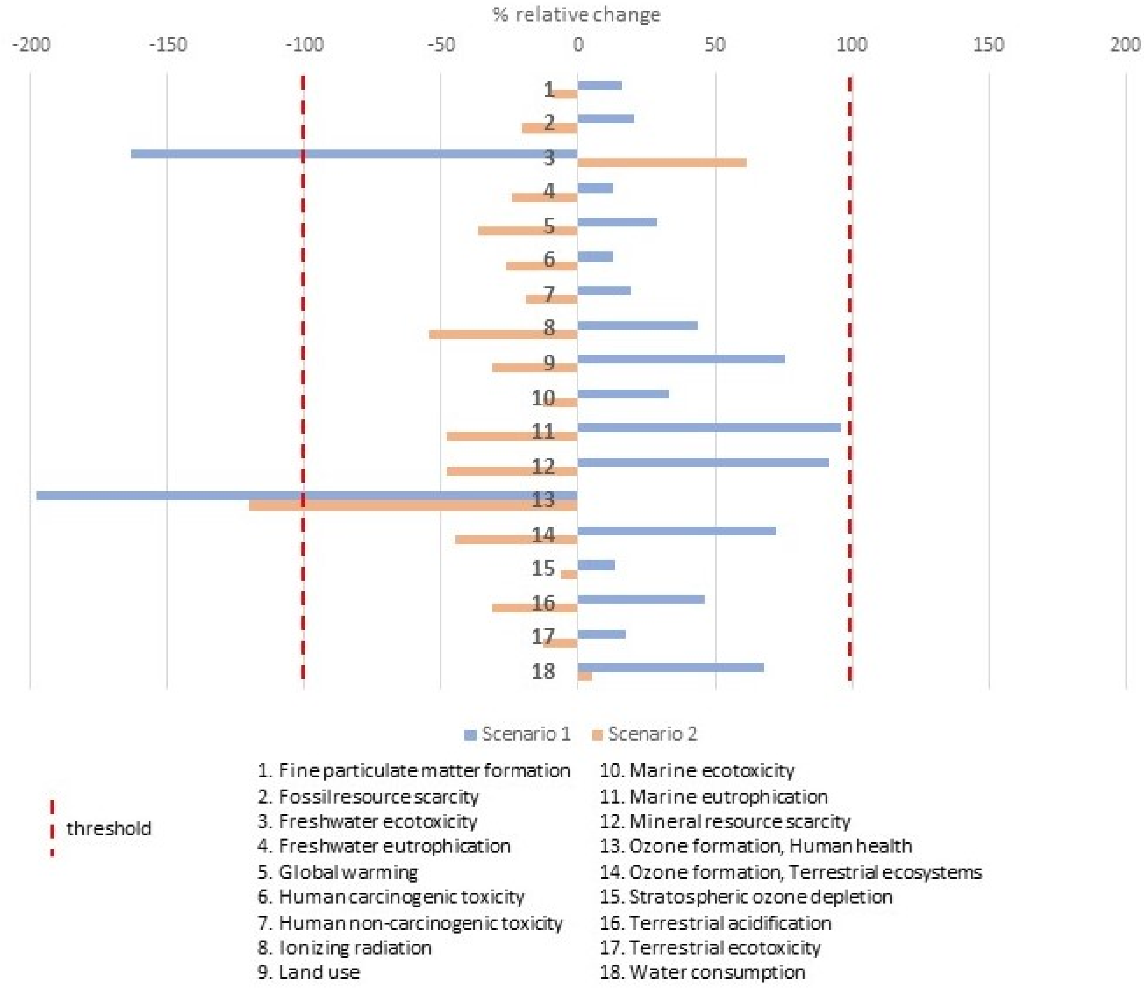


Figure 16: Scenario analysis for steel used in steel core piles

As shown in Figure 16, the both chosen alternatives are sensitive to the model parameter identified. As discussed in the basis of scenario analysis, more than 100% relative change shows that it can have significant influence on the conclusions drawn from the study. The scenario 1 influence the impact score of "Freshwater Ecotoxicity" and "Ozone Formation, Human health". It also almost crosses the threshold in "Marine Eutrophication" and "Mineral Resource Scarcity". The scenario 2 is substantially sensitive to only "Ozone Formation, Human Health". The model parameter identified is also one of the sensitive input parameters from the sensitivity analysis. So, it shows the importance of data quality, representativness and proper handling around this highly sensitive input parameter to draw quality conclusions.

Soil Stabilization: Model Parameter: Cement, blast furnace slag 31-50% and 31-50% other alternative constituents Europe without Switzerland| market for | Conseq, U

- Scenario 1: cement, limestone 21-35% {RoW}| market for cement, limestone 21-35% | Conseq, U

  This alternative has been chosen as the mixture of lime cement is used in the soil stabilisation columns. However, it is not accounting for the use of by products.

- Scenario 2: cement, blast furnace slag, 66-80% {Europe without Switzerland}| market for cement, blast furnace slag 66-80% | Conseq, U

  This scenario is the same process but with different raw material percentage as it is not possible to objectively compare the 50% of kiln dust with relative given percentage of other alternative constituents in SimaPro.

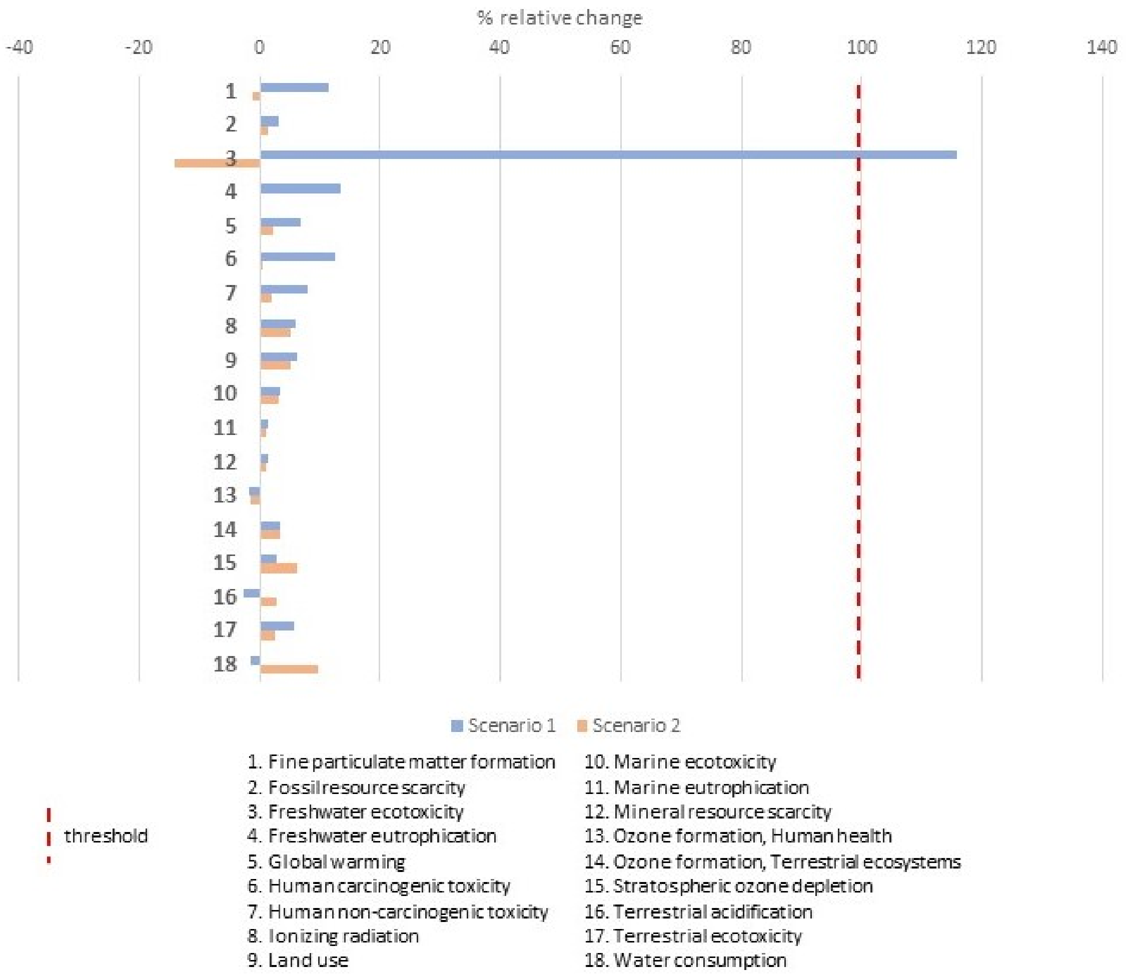


Figure 17: Scenario analysis for cement used in Soil stabilisation

As shown in Figure 17, scenario 1 is sensitive to the model parameter identified, while scenario 2 is not. The scenario 1 hugely impacts "Freshwater Ecotoxicity". The scenario 2 does not influence the output results by much, so it can be use as an alternative to the original input parameter but keeping in mind the technical aspect of it (different raw material percentage). But since one of them passes the threshold value, the model parameter has to be considered as sensitive. Just like in the previous case, the model parameter identified is also one of the sensitive input parameters from the sensitivity analysis. So, it shows the importance of data quality, representativness and proper handling around this parameter to draw quality conclusions.

Sheet Pile Wall: Model Parameter: Steel, low-alloyed, hot rolled {RER}| production | Conseq, U

- Scenario 1: Steel, low-alloyed, hot rolled {GLO}| market for | Conseq, U

This has been chosen as there is no process with “the market for {RER}” in SimaPro, but it’s imperative to mention that the geographical scope (Global) of this process is relatively poor.

- Scenario 2: Steel, low-alloyed {RER}| steel production, electric, low-alloyed | Conseq, U

  This has been chosen as an alternative because there has not been any specific information on the energy used for steel production. This scenario accounts for the possibility that the steel was produced with electricity.

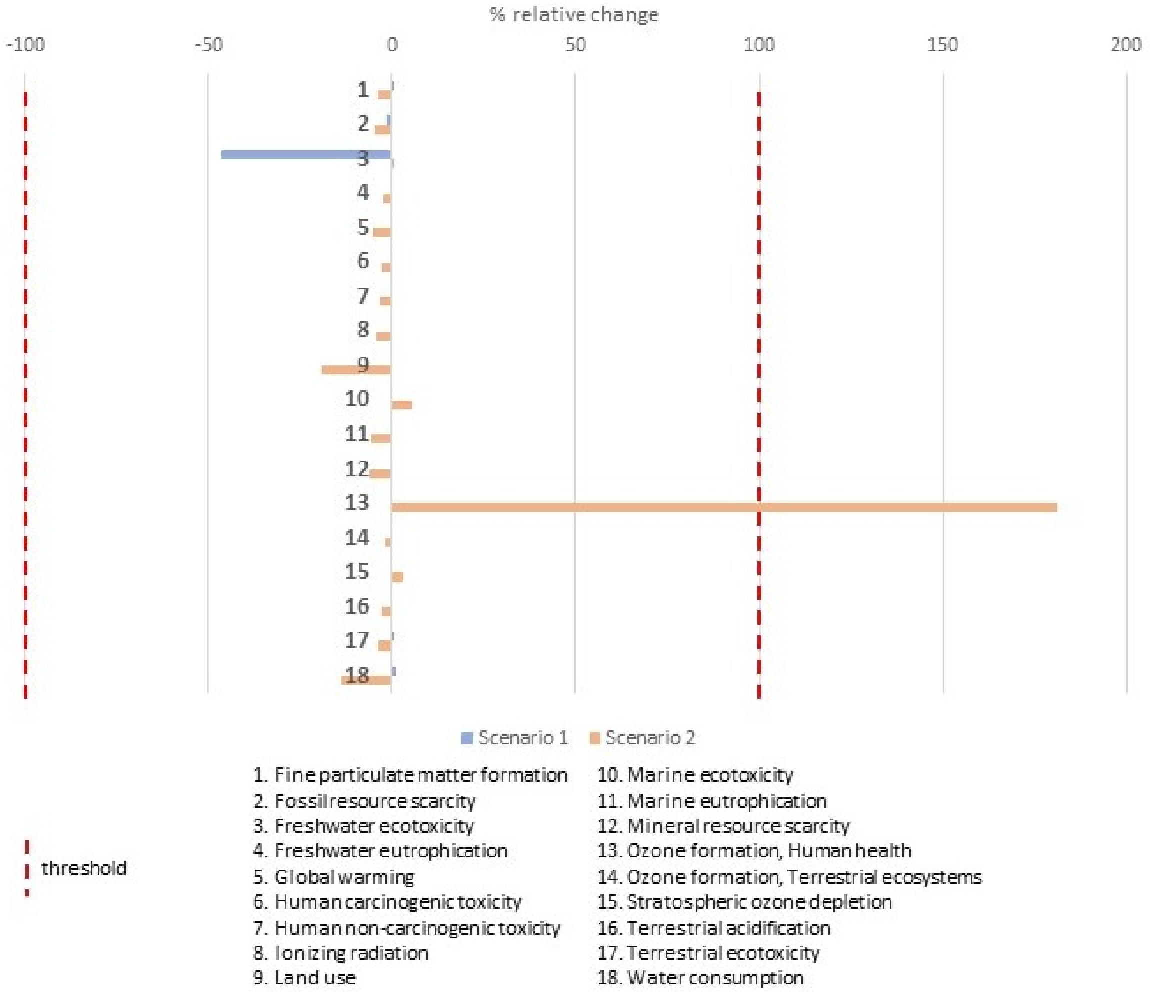


Figure 18: Scenario analysis for steel used in Sheet pile walls

As shown in Figure 18, the model parameter identified can be classified as a sensitive parameter as scenario 2 crosses the threshold value. The scenario 1 does not changes the result by much, so, it can act as an alternative considering the technical representativeness of process. The scenario 2 is extremely sensitive to "Ozone Formation, Human Health". Just like the two previous cases, the model parameter identified is also one of the sensitive input parameters from the sensitivity analysis. So, it shows the importance of data quality, representativness and proper handling around this parameter to draw quality conclusions.

Excavation of masses: Model Parameter: Transport, freight, lorry >32 metric ton, euro6 {RER}| market for transport, freight, lorry >32 metric ton, EURO6 | Conseq, U

- Scenario 1: Transport, freight, lorry 16-32 metric ton, euro6 {RER}| market for transport, freight, lorry 16-32 metric ton, EURO6 | Conseq, U

  This has been chosen as an alternative in terms of the size of the truck and lorry with the same geographical and technological scope. No other scenario has been chosen as the data specifies at least 16 metric ton of excavated masses.

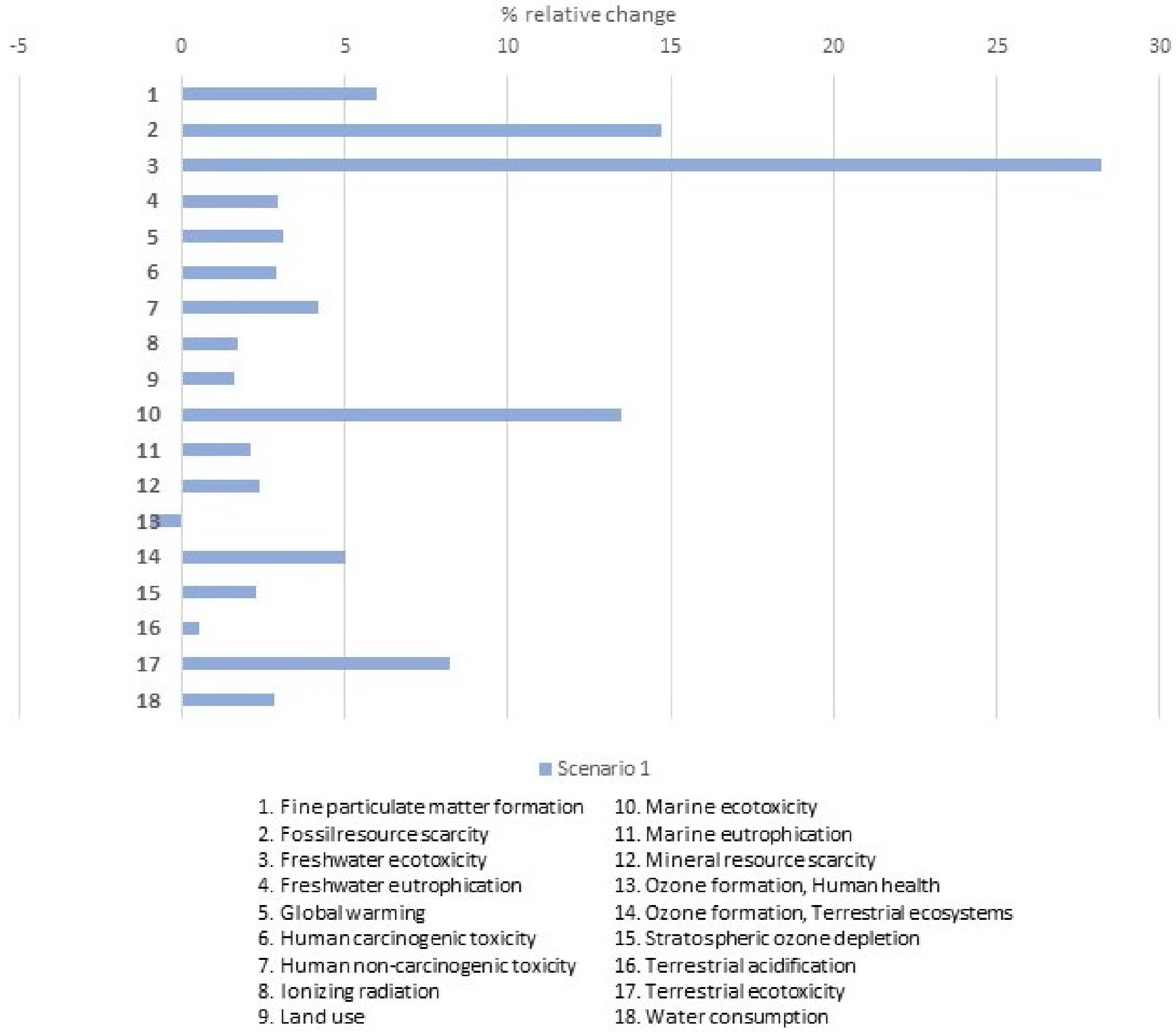


Figure 19: Scenario analysis for the type of truck used in the excavation of masses

As shown in Figure 19 the alternative scenario of the truck type with 16-32 metric tons, does not cross the threshold value, so it is not identified as sensitive to the model parameter. It can be used as an alternative to the model parameter identified as it's not changing the results significantly. But it's important to consider the representativeness of the carrier/vehicle type used in the process as well.

6.2 Interpretation of weighted midpoint and sensitivity analysis

The weighted mid-point analysis has been done by multiplying the characterised baseline results with the weighted factors for each impact category used by ReCiPe 2016 method to calculate the endpoint results [40]. By doing so, the detailed impacts of each unit process can be laid out in context of how much they are contributing to the endpoint results.

In the analysis of weighted midpoint results, it has been detected, that the process of steel core piles is the most contributing when it comes to the protection area of human health (Figure 22). It is also most dominantly contributing to the protection areas ecosystem and resource scarcity (Figure 26).

As shown in figure 14, the amount of steel, which was changed in the perturbation sensitivity analysis is sensitive in regards to different impact categories, which have been explained in the following:

The impact category fine particular matter formation is highly affected by the amount of steel and is at the same time very relevant, as it contributes highly on human health (Figure 22). Impact category "Human carcinogenic toxicity" has been identified as sensitive in the perturbation approach of steel and at the same time is being highly impacted in the weighted midpoint and endpoint results. It therefore has been identified as relevant.

Furthermore, freshwater eutrophication is a relevant impact category as it is affected by the type of steel and and at the same time the most affected impact category in the weighted results of steel core piles. The amount of steel in steel core piles is also sensitive (NSC very close to 0.5 has been assumed to be sensitive in this case) in regards to freshwater ecotoxicity, and also plays a significant role in the contribution of the endpoint category of ecosystem.

As the type of steel in the process of sheet pile walls has been identified as sensitive for ionizing radiation, but it’s not significantly impacted in the weighted midpoint results, and thus the effect is not accounted as relevant. The same applies to the type of cement used for soil stabilization (Table 7), as the parameter is sensitive for ionizing radiation, but does not get affected in a relevant extent to the weighted midpoint results.

As shown in the scenario analysis the steel type used in steel core piles is sensitive for freshwater ecotoxicity, marine eutrophication and ozone formation, human health. As freshwater ecotoxicity is also impacted to the overall contribution of steel core piles, the type of steel is a relevant parameter in regards to the endpoint of ecosystem. The impact category freshwater eutrophication is not scenario sensitive (Figure 16), but significantly impacted to the overall impact of steel core piles (Figure 24) Consequently, for this impact category it is not the type of steel, but the quantity of steel which has a significant impact on freshwater eutrophication.

In scenario 2 the type of steel has been sensitive in regards to the ozone formation, human health (Figure 16), but is not a relevant because, the overall contribution of steel core piles on that impact category is not significant (Figure 22). Furthermore the type of steel is also sensitive in regards to marine eutrophication. In the process of steel core piles, marine eutrophication is the most dominant impact category affected (most contributing to the total)(Figure 25).

In regards to the type of steel in the process of steel core piles, the analysis shows a sensitivity for the impact category ozone formation, human health, but it has not been accounted as relevant, since it is not getting significantly affected in the overall weighted midpoint results of steel core piles.

For the type of cement in unit process "soil stabilization", the scenario 1 is sensitive to the impact category fresh water eutropication and it’s also being reflected in the weighted midpoints for freshwater eutophication (Figure 24). It is imperative to notice, this is the most impactful category even when the emissions into the soil from lime cement columns have not been considered in the model.

The amount of steel in "sheet pile wall" is only sensitive to impact category ionizing radiation (Figure 14) while it does not reflect in weighted midpoint analysis (Figure 22). For the type of steel in sheet pile wall, it is sensitive to the impact category ozone formation (Figure 19) but it does not reflect in the weighted midpoint analysis (Figure 22).

6.3 Impact Method analysis

To check the uncertainty from the impact assessment method chosen (ReCiPe (H) 2016) for the baseline results, another impact assessment method (IMPACT World+) has been chosen and their results has been compared. Below the process contribution in each impact category can be seen from the results of IMPACT World+ assessment method:

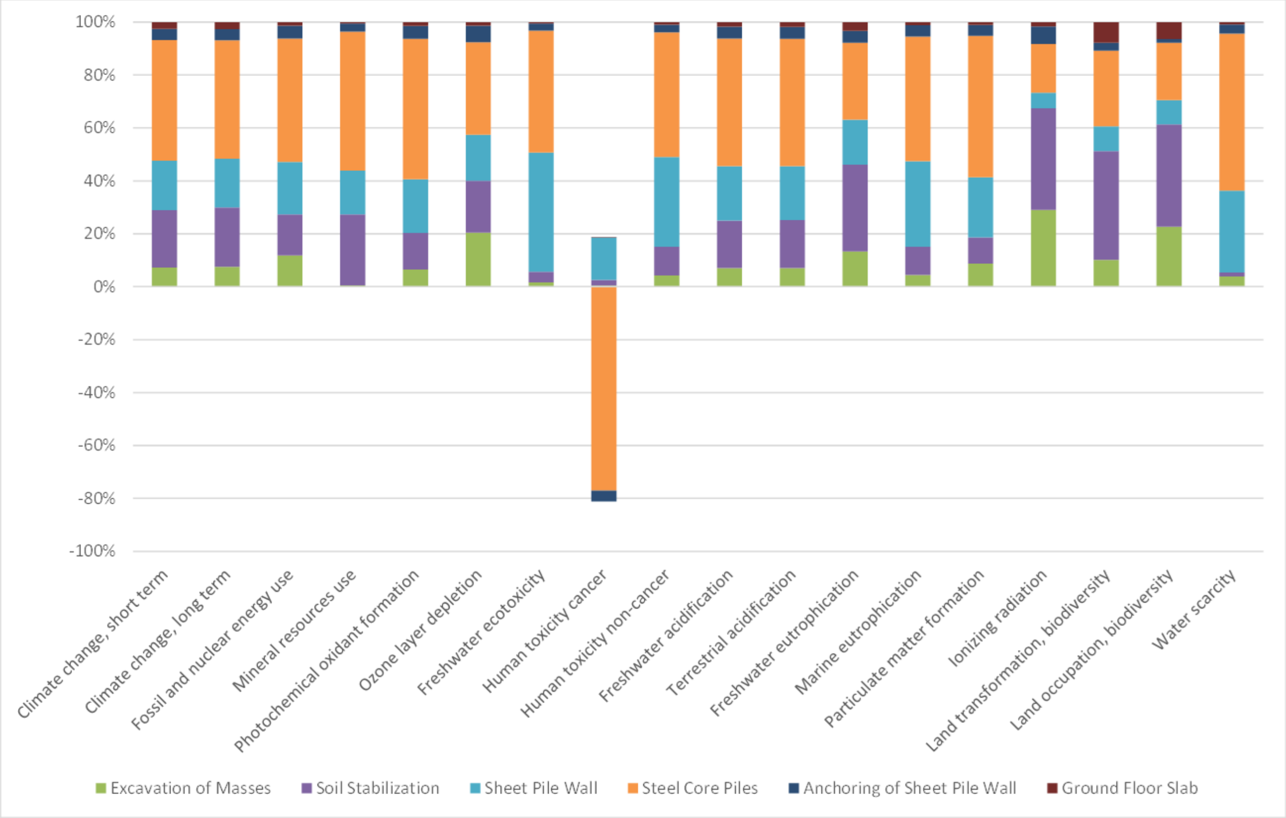


Figure 20: Process contribution from the IMPACT World+ LCIA method

From Figure 20, it can be seen that the impact categories, "ionizing radiation", "sheet pile wall" and "steel core piles" have a positive contribution. Specifically for the unit process "steel core piles", it's very substantial. In the water scarcity, the process contribution of "ground floor slab" is relatively much lower, while, "steel core piles" have a relatively large impact.

These changes in the impact categories can not be objectively compared as the method by which their characterised values are determined might differ. But after considering the exceptions and looking at the general trend of process contribution of each unit process in mutual impact categories, it can be stated that the same conclusions can be drawn out of both methods with some exceptions (e.g.: Ionizing radiations).

6.4 Qualitative Uncertainty Check

In the chapter of the qualitative uncertainty check, in a first step the representative of data (section 6.4.1) is discussed, with a focus on the unit processes and assumptions. In the second step in the key data analysis (section 6.4.2), these results are taken into relation of the sensitivity analysis.

6.4.1 Representativeness of data

In the following section, the representativeness of the individual unit inventory processes used in the model and the adjustments made inside default process to make them more relevant has been described in details. The table with the corresponding subjective magnitude of "representativeness" can be found in the Appendix A.1.1.

Soil stabilisation

Material - stabilisation columns
For the Material - stabilisation columns used in the soil stabilization (soil stabilisation-columns) the material process

“Cement, blast furnace slag 31-50% and 31-50% other alternative constituents {Europe without Switzerland}| production | Conseq, U” was used. The actual material used for soil stabilisation in Oslo is “Multicement”, which is a material in which in the production limestone is replaced by cement kiln dust (CKD) [22]. From the EPD, neither precise background data on the shares of different components replaced, nor data on emissions and output to technosphere from Multicement were available. Consequently, an alternative but related material process was chosen, which describes a material process of average European cement production (without Switzerland) from cradle-to-gate (without packaging and administration) and uses electricity and heat value for Europe in the input to technosphere. The geographical representativness is assumed to be suitable for the stabilisation column implementation in Oslo. In material input to technosphere, limestone is considered, but also as part of 31-50% alternative constituents. By using this material process, a higher environmental impact is expected, in comparison to the actually used multicement due to the missing supplementation by matrerials like CKD. Consequently, the material process is only to a limited extent representative for this project and is potentially adding significant uncertainty to the results. Also on the technological level it is accounted to be low representative for the current analysis, since the data is valid from 2005 to 2020, has a Technology level of 3 and is a significantly different material. Technological innovations like multicement have been introduced to the market since then.

Machine operation

Regarding the machine operation for the soil stabilisation processs, the consumption of fuel was calculated by total amount of fuel and total hours of machine running, which were provided by NGI and the average density of Diesel [23] to convert it into a consumption value in l/h. Since the calculated Diesel consumption was significantly higher than the machine operation processes available as default in SimaPro, the highest category “Machine operation, diesel, >= 74.57 kW, high load factor {GLO}| machine operation, diesel, >= 74.57 kW, high load factor | Conseq, U” was chosen and adjusted in the Diesel input value for the input from technosphere. Consequently, the SimaPro process is only to a limited amount representative and potentially adds uncertainty to the results. The dataset is modelled for a global context and represents the operation of construction/industrial machines. The inputs from technosphere are mainly based on global processes, but also take into account the “Lubricating oil {RER}| market for lubricating oil | Conseq, U” for the European context. The same is valid for the output to technosphere, as “Waste mineral oil Europe without Switzerland| market for waste mineral oil | Conseq, U” is considered. Consequently, it seems appropriate to assume geographical representativness. The underlying dataset is from 2014 and extrapolated to 2020 with adjusted uncertainties according to the time frame. Additionally, it represents the average current technology for construction and industrial machineries with a technology level of 3 and is therefore considered as adequately representative for this study.

Material transport

Due to the high calculated values of material transport of cement (Mass-Distance = 195789.1078 tkm, subsection A.1) the biggest truck size, “Transport, freight, lorry >32 metric ton, EURO6 {RER}| transport, freight, lorry >32 metric ton, EURO6 | Conseq, U” was chosen. The process displays a “service of 1tkm freight transport in a lorry of the size class > 32 metric tons gross vehicle weight (GVW) and EURO6 emissions class” [7] and the inventory is modelled for Europe. The transport process in SimaPro accounts for the entire transport lifecycle including the construction, operation, maintenance, end of life of vehicles as well as road infrastructures. Fuel consumption and emissions are for average European journeys and load factors. The input from technosphere for materials/fuel is dominated by European over global inputs (4/5). Only the “Road {GLO}| market for | Conseq, U” is considered as global input from technosphere, but adjusted with assumptions for European road transport service. Also the outputs (emissions to air) are dominantly european specific (mostly based on EMEP/EEA -2013 guidebook). The dataset is based on literature in 2013 and has been extrapolated to 2020, and the uncertainty has been adjusted accordingly. The process is accounted to be still valid for the model process. In the technological scope, the dataset is based on technological levels on EURO standards in regards to emissions, Diesel and Diesel engines. A technological level 1 is stated. Consequently, the transportation process is accounted as representative on temporal ,geographical and technological scope and is potentially not adding significant uncertainty to the results.

Machine transport

Regarding machine transport, the process "Transport, freight, lorry >32 metric ton, euro6 {RER}| market for transport, freight, lorry >32 metric ton, EURO6 | Conseq, U" was chosen in SimaPro. The decision was based on the data provided on Seabrokers website with values for excavators weight. The head office of “Seabrokers” (providing the machines) is situated in Norway and therefore a model process representing European standards was chosen. For the transportation, in general an emission class of EURO6 was determined in cooperation with NGI for all involved vehicles. The facts about the transport processes when it comes to input from technospere and output are similar to the process descibed in Material transport of soil stabilisation (see above) and are assumed to be representative in temporal, technological and geographical scope for machine transport of the study case. Consequently, no significant uncertainty addition is expected from this process.

Excavation of masses

Machine operation

To model the machine operation, the precise value for the total volume of excavated masses was used and the process "Excavation, hydraulic digger {RER}| processing | Conseq, U “ was implemented in the SimaPro Model, since this process reflects the closets approximation to an excavator used at the pit in Oslo. The dataset is based on a LCA study "Oekoinventare von Energiesystemen 1996". The Diesel consumption and the emmissions are updated using the Swiss ´Offroad Database´and applied to year 2000. The database has been extrapolated from year 2001 to 2020 and uncertainty has been adjusted accordingly. The inventory - Inputs from nature and outputs to technosphere - are modelled for Europe. With a technology level of 3 the process is representing the average current technology for one typical machine representing the industrial machinery of hydraulic diggers. In the documentation of the process, it is also stated that the uncertainty is quite high in certain environmental inventories. Since the technology since 1996 probably changed in the offroad machinery technology and the process of an hydraulic digger also does not precisely fit to the excavator used at the excavation pit in Oslo, the temporal and technological representativness is probably not very good and adding uncertainties to the results. The geographical representativness is assumed to be suitable.

Transport of masses by truck

Due to high calculated values for Mass-Distance of excavated masses (23103858.99 tkm), and information on waste-mass contribution shown in Table 14, the inventory process "Transport, freight, lorry >32 metric ton, euro6 {RER}| market for transport, freight, lorry >32 metric ton, EURO6 | Conseq, U" was chosen. The detailed description of the database and temporal extrapolation of that process can be seen above (Material transport in soil stabilisation). The process is assumed to be representativness in global, technological and temporal context, potentially not adding significant uncertainty to the results.

Transport of masses by ship

For the waste transport of excavated masses (contaminated soil), the inventory process "Transport, barge ship, bulk, 5500t, 80%LF, empty return/GLO Mass" was used for the model. This process represents the transport of 1tkm per barge in an global average. The fuel consumption is based on a publication of CE Delft in 2008 and the emissions due to fuel combustion of water transport are based on reports in 2012 and was taken from the AGri5 library, since no comparable process was available in Ecoinvent.

The empty return was chosen, since the ship is going to a landfill island called "Langøya", where no materials are likely to be reloaded. The load factor of 80% was chosen, since the ship is not exclusively transporting masses from the excavation pit, but might contain waste from other sources as well. The size of the ship was based on the carrying capacity of the HAGLAND hybrid ship [24].

The geographical scope is appropriate and the temporal representativness seems to adequately represent the current situation. When it comes to the technological level, the inventory process might add significant uncertainties to the results, since the process was adjusted in emissions based on information found on the hybrid technology of HAGLAND [24]. The new technology has a reduced Diesel consumption as well as reduced CO_2 emissions of 20%. Furthermore the NOx emissions are reduced by 85%.

Transport of machines

For the transport of machines in the process of "excavation of masses", the inventory process "Transport, freight, lorry >32 metric ton, euro6 {RER}| market for transport, freight, lorry >32 metric ton, EURO6 | Conseq, U" was chosen.

Sheet Pile Walls

Material steel

For the material steel, the material process “Steel, low-alloyed, hot rolled {RER}|production|Conseq,U” was chosen. The process is geographical representative for the average of World and European steel production mix accounting for a mix of differently produced steels and hot rollings. The input from technosphere in this material process consist of “Steel, low-alloyed {GLO}| market for | Conseq, U” and hot rolling, steel Europe without Austria| hot rolling, steel | Conseq, U , which is valid for the type of steel (S355GP) used for the sheet pile walls at the excavation pit [25]. Consequently, the material process is defined to be geographically highly representative for the steel used in the excavation pit in Oslo. As reported in the documentation of the process, the dataset for the material process in SimaPro was created in 2002 and extrapolated to 2020 and the uncertainty has been adjusted accordingly. Since, we are looking at this LCA data in 2021, the end date of the validation was 31/12/2020, but no major innovations are expected on the material production of steel in Europe, the process is declared as representative on a temporal scope. It is assumed that the process will be suitable in representativness on technological scope, because there may have been small changes and developments on technological scale since 2002 , but on average the technology seems still adequatly represent current steel production technologies.

Transportation of material

Regarding the transportation of material, it was decided to take “Transport, freight, lorry 16-32 metric ton, euro6 {RER}| market for transport, freight, lorry 16-32 metric ton, EURO6 | Conseq, U”. The truck size was decided based on the fact that a certain shape needs to be accounted for the sheet pile walls [28]. There are 3 different types of sheet pile walls used (AZ19-700, AZ25-800, AZ12-770), which have different sizes and shapes. Trucks of size 16-32t were chosen to account for the different volumes/shapes of sheet pile walls. The dataset “Transport, freight, lorry 16-32 metric ton, euro6 {RER}| market for transport, freight, lorry 16-32 metric ton, EURO6 | Conseq, U” has the same underlaying dataset, data desciption and extrapolation frame as "Transport, freight, lorry >32 metric ton, euro6 {RER}| market for transport, freight, lorry >32 metric ton, EURO6 | Conseq, U" used for material and machine transport in soil stabilisation (see detailed describtion above). Consequently, the process in SimaPro is assumed to be representative on geographical, temporal and technological scope not adding significant uncertainties to the results.

Transportation of machines

In the process of transporting the machines used for the implementation of the sheet pile walls to the excavation pit, “Transport, freight, lorry >32 metric ton, EURO6 {RER}| transport, freight, lorry >32 metric ton, EURO6 | Conseq, U”. As the machines are also provided by "Seabrokers" [26]. The truck size could be estimated based on machine information (See chapter assumptions subsubsection 4.5.1). As for other transport processes (see detailed description above), the inventory process is accounted as representative on temporal, geographical and technological scope, probably not adding significant uncertainties to the results.

Machine operation

The machine operation for the implementation of sheet pile walls was modelled with the inventory process “Machine operation, diesel, >= 74.57 kW, high load factor {GLO}| machine operation, diesel, >= 74.57 kW, high load factor | Conseq, U” based on provided machine hours (3 machines running 42 hours a week for 7 month). The inventory process is described in detail in text above (machine operation - soil stabilisation).

Anchoring

Material

The inventory process "Steel, unalloyed {RER}| steel production, converter, unalloyed | Conseq, U" was chosen for the model based on the provided types of steel (S235JR, S355J2H) in the anchoring process. The inventory process is modelled for Europe and the data represent the production of primary steel (carbon, unalloyed). Data are primarily taken from the IPPC Best Available technology report from the European Commission in 2013, taking direct measurements at blast furnace plants across Europe. The values represent averages and are not extrapolated, but valid until 31/12/2023. As the input from technosphere in the scope of materials covers Europe and global values, the electricity/heat input is represented as European value "Electricity, medium voltage {RER}| market group for | Conseq, U", but the inventory process does not take background transportation into consideration. Also the outputs to technosphere in this process are exclusivley modelled as European and Swiss. The inventory process represents highly the temporal, geographical and technological standard of the material production, which is used in the case study and is therefore not expected to add significant uncertainty to the result.

Transport of material

The transportation of material used for the anchoring (wires, anchor heads, hollow steel tubes, wailing) are modelled with the inventory process "Transport, freight, lorry 16-32 metric ton, euro6 {RER}| market for transport, freight, lorry 16-32 metric ton, EURO6 | Conseq, U". Due to very different shapes, volumes and sizes of the different anchor parts, the lorry 16-32 metric tons was taken. The detailed description of the inventory transport process can be seen above (material transport in soil stabilistaion), as it is the same dataset as for "Transport, freight, lorry >32 metric ton, euro6 {RER}| market for transport, freight, lorry >32 metric ton, EURO6 | Conseq, U". As for the other transportation processes, it is assumed to be representative on geographical, temporal and technological scope and not adding significant uncertainty to the results.

Machine operation
Regarding the machine operation of the anchoring process, the total amount of machine hours, were provided by NGI and modelled with the inventory process “Machine operation, diesel, >= 74.57 kW, high load factor {GLO}| machine operation, diesel, >= 74.57 kW, high load factor | Conseq, U”. The inventory process was described in detail in the chapter above (Machine operation - soil stabilisation). It seems appropriate to assume geographical representativness, since the inventory process is modelled for European context. Since the underlying dataset extrapolated to 2020 with adjusted uncertainties according to the time frame and represents the average current technology for construction and industrial machineries, it is considered as adequately representative for this study.

Transport of machines
In the process of transporting the machines (drilling rigs) used for the implementation of the anchoring process, “Transport, freight, lorry >32 metric ton, EURO6 {RER}| transport, freight, lorry >32 metric ton, EURO6 | Conseq, U”. As the machines are also provided by "Seabrokers"[26]. The truck size has been estimated based on machine information (See chapter assumptions subsubsection 4.5.1. As for other transport processes (see detailed description above), the inventory process is accounted as representative on temporal, geographical and technological scope, probably not adding significant uncertainties to the results.

Material Cement
For the cement used in the anchoring process the inventory process "Cement, Portland {Europe without Switzerland}| market for | Conseq, U" has been used for the model.The inventory is modelled for Europe without Switzerland and uses exclusiveely input to technosphere from European scope. As it takes "Cement, Portland {Europe without Switzerland}| production | Conseq, U" as input to technosphere, which represents the cradle to gate production of cement , with electricity from Europe (without Switzerland) and emissions to air, plus the background transportation for the particular market of cement production, the process is accounted as geographically representative. The dataset was extrapolated from 2009 to 2020 and uncertainties have been adjusted accordingly. The cement production technology may have changed since 2009, but the temporal scope still is accounted as appropriate and the technology level seems to be adequately representative.

Transportation of cement
In the process of material transport (cement) used for the implementation of the anchoring process, the inventory process “Transport, freight, lorry >32 metric ton, EURO6 {RER}| transport, freight, lorry >32 metric ton, EURO6 | Conseq, U” has been used. The truck size has been based on the calculated mass of cement used in the process (see subsection A.1. As for other transport processes (see detailed description above), the inventory process is accounted as representative on temporal, geographical and technological scope, probably not adding significant uncertainties to the results.

Steel Core Piles

Material steel The inventory process "Steel, unalloyed {RER}| steel production, converter, unalloyed | Conseq, U" was chosen for the model based on the provided types of steel (S355J2/S355J0) from EPD [25]. The inventory process is described in detail above (see Material steel - Anchoring). The inventory process is highly representative for temporal, geographical and technological standard of the unalloyed steel production, which is used in the case study and is therefore not expected to add significant uncertainty to the results.

Material - concrete
For the concrete used in the process of steel core piles to fill the gap between steel core piles and casings, the inventory process "Concrete, normal {CH}| market for | Conseq, U" was used for the model. The inventory is modelled for Switzerland. As is takes "Concrete, normal {CH}| unreinforced concrete production, with cement CEM II/A | Conseq, U" as input to technosphere, which represents the production of unreinforced concrete with cement CEMII/A from primary aggregates and swiss dominated inputs from technosphere including electricity/heat, the process cannot be accounted as geographically representative and might add significant uncertainties to the results. The dataset was extrapolated from 2011 to 2020 and uncertainties have been adjusted accordingly. The concrete production technology may have changed since 2011, but the temporal scope still is accounted as appropriate and the technology level seems to be adequately representative.

Transport of material - steel

Regarding the transportation of steel core piles, the shapes of the piles and the casings was considered as a factor. Consequently, the smaller type of truck "Transport, freight, lorry 16-32 metric ton, euro6 {RER}| market for transport, freight, lorry 16-32 metric ton, EURO6 | Conseq, U" was chosen. The detailed description of the inventory transport process can be seen above (material transport in soil stabilisation), as it is the same dataset as for "Transport, freight, lorry >32 metric ton, euro6 {RER}| market for transport, freight, lorry >32 metric ton, EURO6 | Conseq, U". As for the other transportation processes, it is assumed to be representative on geographical, temporal and technological scope and not adding significant uncertainty to the results.

Transport of material - concrete

Regarding the transportation of concrete, "Transport, freight, lorry >32 metric ton, euro6 {RER}| market for transport, freight, lorry >32 metric ton, EURO6 | Conseq, U" was chosen based on the total amount of concrete calculated (see subsection A.1. The detailed description of the inventory transport process can be seen above (material transport in soil stabilisation), as it is the same inventory process. As for the other transportation processes, it is assumed to be representative on geographical, temporal and technological scope and not adding significant uncertainty to the results.

Transport of material - excavated masses In regards to the transportation of waste material (excavated masses from drilling sludge), a quite big Mass-Distance was calculated (113355 tkm), and therefore "Transport, freight, lorry >32 metric ton, euro6 {RER}| market for transport, freight, lorry >32 metric ton, EURO6 | Conseq, U" was used to model the process. The detailed description of the inventory transport process can be seen above (material transport in soil stabilisation), as it is the same inventory process. As for the other transportation processes, it is assumed to be representative on geographical, temporal and technological scope and not adding significant uncertainty to the results.

Transport of machines

As for the other machine transportation processes, the machines were delivered from "Seabrokers" and the type of truck was decided based on the number of machines and weight information of the drilling rigs [26]. As for machine transportation in the processes, the model was built with the inventory process "Transport, freight, lorry >32 metric ton, euro6 {RER}| market for transport, freight, lorry >32 metric ton, EURO6 | Conseq, U". The detailed description of the inventory transport process can be seen above (material transport in soil stabilisation), as it is the same inventory process. As for the other transportation processes, it is assumed to be representative on geographical, temporal and technological scope and not adding significant uncertainty to the results.

Machine operation

To model the machine operation for the process of steel core piles, the machine hours were used in the inventory process of "Machine operation, diesel, >= 74.57 kW, high load factor {GLO}| machine operation, diesel, >= 74.57 kW, high load factor | Conseq, U". The inventory process is described in detail in text above (machine operation - soil stabilisation), as the same type of machines have been assumed as in that process.

Ground floor slab

Since only parts of the processes, which are needed to implement a ground-floor slab are modelled, the process cannot be seen as representative and might cause significant uncertainties in the results. The processes "transportation of machinery" and "Machine operation" are not implemented in the model.Furthermore, no steel grids are implemented in the implementation of the ground floor slab. The volume of concrete and lean concrete was based on assumptions and external sources on density of these materials (subsubsection 4.5.1).

Material - lean concrete

As already explained in the assumptions subsubsection 4.5.1 the groundfloor slab is modeled with a layer of "Lean concrete". To model the material of "lean concrete", the inventory process "Lean concrete {CH}| market for | Conseq, U" was used. The inventory is modelled for Switzerland, with a dataset from 2011, which is extrapolated to 2020. It accounts for the production of lean concrete with CEM II/A and CEM II/B is a ratio of 1:3 from primary aggregates for the swiss production. The inventory process is likely to be representative of production of lean concrete for Europe, as the standards in Switzerland are also very high. The temporal scale seems appropriate, and the current average technology is representative for current average technology. Both the temporal and technological representativeness of the chosen method do not potentially contribute to significant uncertainty in the results.

Material - concrete

For the concrete used in the process of building the ground floor slab, the inventory process "Concrete, normal {CH}|

market for | Conseq, U" was used for the model. As already described in detail in "Steel Core Piles" (see above), the inventory process also cannot be accounted as geographically representative and might add significant uncertainties to the results. The temporal scope still is accounted as appropriate and the technology level seems to be adequately representative.

Transport of material

For the transportation of the materials necessary for the ground-floor slab, the inventory process "Transport, freight, lorry >32 metric ton, euro6 {RER}| market for transport, freight, lorry >32 metric ton, EURO6 | Conseq, U" has been used in the model. The detailed description of the data supporting this precise transportation, see above. To calculate the total weight of the "lean-concrete and the concrete, density values from external sources have been used [39].

6.4.2 Key data analysis

The key data analysis has been performed by mapping out the sensitivity of each input parameter (Appendix: Table 22) with respect to it's quantitative data representativeness score (Appendix A.1.1 Table 6) .

The identified key data is:

1. Soil Stabilization: Amount of cement
2. Sheet Pile Wall: Amount of steel
3. Steel Core Piles: Amount of steel

These processes have also being identified as model parameters in scenario analysis. This reinforces the significance of data quality and careful consideration while modelling these parameters.

Figure 21: Key-Data Analysis

7 Conclusions, Limitations and Recommendations

The study has been executed on the unit process level, to identify the hotspot single unit process and it´s major environmental impacts. To conclude this LCA, the conclusion (section 7.1, limitations (section 7.2) and recommendations (section 7.3) of this study are displayed in this chapter.

7.1 Conclusions

After performing the LCA as well as conducting sensitivity and uncertainty checks, within the following subchapter, the learning's will be presented:

I. In the establishment of the LVB excavation pit, the process with the significantly biggest environmental impact throughout midpoint and endpoint impact categories are steel core piles. It is therefore identified as environmental hotspot of the analyzed process system.

II. There is a clear hierarchy in terms of which processes are more impactful and that is: steel core piles, sheet pile wall, soil stabilization, excavation of masses, anchoring of sheet pile wall and ground floor slab. How significant is the difference between each process in total terms has been discussed in section 6.

III. Regarding substances contribution, global warming impacts are mainly driven by emissions of carbon dioxide (CO2), which contributes to 90% of the total impacts. The biggest contribution processes to CO2 emissions are steel core piles (44%) and soil stabilization (22%). Terrestrial toxicity as well as freshwater and marine ecotoxicity are the most impacted by copper (around 50%), which comes mainly from steel core piles and sheet pile wall processes. Regarding mineral and fossil resource scarcity, iron and nickel and coal and oil are the most impactful substances respectively.

IV. The external normalization performed for the midpoint results show that the results are in an order of magnitude that is reasonable with the magnitude of the analysed reference flow of one excavation pit.

V. From the weighted results in terms of the three endpoint impact categories, it is distinct that human health is most impacted, with a total impact which counts for 95% of the total impact. The Ecosystem is impacted 3.8% of total impact and the resources are following with 2%. This distribution of the impacts is very similar across all analysed processes, however the magnitude of the impacts is different and follows the previously described hierarchy.

VI. The overall environmental performance of steel core piles is mainly determined by the type of steel used in production stage. It has an extreme variable impact on freshwater ecotoxicity and ozone formation/human health. It therefore can be considered an important environmental performance indicator for the LVB excavation pit.

VII. The type of steel and amount used in steel core piles, in Sheet Pile walls as well as the type of cement and amount used in soil stabilisation are important environmental key parameters are the most sensitive parameters. They have significant impact on impact categories "Ozone formation/human health" and "Freshwater ecotoxicity" respectively.

VIII. The ground-floor slab is the least environmentally impactful process in the comparison of processes needed for the establishment of the LVB excavation pit, but is also the least representative process Table 6.

7.2 Limitations

In general, there are limitations in representing real-world problems, processes and systems in a model. The complexity of systems has to be broken down into some kind of applicable generalization and simplification to create a model. Thus, the major limitation of the study has been the modeling approach itself. It only can represent the reality under simplified conditions and therefore the assumptions made while modelling the unit processes are of great relevance. As the current study has been a decision context situation of C1, hence it has by definition limitations in the function of decision support and has not been created for this purpose.

While developing the model and unit processes, the assumptions made subsubsection 4.5.1 have lead to associated limitations of the study, which are mentioned below:

I. The study has been carried out under the assumption that the technology and materials of the construction works for the excavation pit are on the current technology level (section 3.5) and would not significantly change in close future. Hence, any major innovative new technologies in the practice would render the results obsolete. In this context, the limitations arising from the uncertainty of assumptions made to fit the process used in the model for materials (Multicement) and transportation (Hybrid ship) need to be mentioned.

II. The analysis has been created under the assumption that the material production and delivery mainly would take place in Europe (see scope definition and section 3.5).

III. Data implemented in the model have been limited in their representativness subsection 4.4. Furthermore, the implementation of the model in SimaPro has limitations on representing the very processes in reality subsubsection 6.4.1.

IV. In the implementation of the inventory processes, care has been taken to choose mainly "market for" processes, which also take into account background processes for transportation and production. In some cases this has not been possible (The inventory processes are described in detail in chapter subsubsection 6.4.1). For these inventory processes, no background system (production and /or transportation) has been accounted in the model.

V. Whenever country specific data/local data has not been available, the geographical scope for the processes was either based on nearby countries like Switzerland or modeled in a priority of {RER}/{CH}/{GLO}/{RoW}, to reflect best the Norwegian context within the European market.

VI. In the current model simulation “Emissions into soil” and "groundwater leakage" caused by lime cement columns in the process of “soil stabilization” has not been covered.

VII. In the process of “excavation of masses” the impact of the contaminated masses after transporting it to the landfill (leaching, outgasing etc.) has not been considered.

VIII. In the process of “excavation of masses” only the transport processes have been considered, but the loading/unloading processes, from trucks and ships have been neglected.

IX. In the case of missing or incomplete data, Environmental Product Declarations (EPDs) were used. In the work with the EPDs, however, there was no background data, but only material types, dimensions and categorization have been used.

X. The main goal of the LCA study has been to identify the process with most environmental impact in the execution of the excavation pit. Since the data quality and transparency for each unit process differs significantly, the conclusions drawn in the report might differ by some extend in the real world.

XI. With the implemented system boundaries of this study, the use phase and disposal stage of the materials have not been considered and therefore limitations are to be mentioned in the holistic consideration of the geotechnical processes.

XII. The process of groundfloor slab is not representative and dominantly created based on assumptions, missing major processes and materials. Therefore, statements about the environmental impact of the ground floor slab can only be made to a very limited extent.

7.3 Recommendations

As a general statement, Life Cycle Assessment of geotechnical works is still a very young field of study and critical gaps in current knowledge and practice need to be closed by more research in that field. Since the structure of the study is not intended to support decisions, it is placed in the decision-context C1. Therefore, it is only possible to give recommendations in a very limited context. In the following, broad recommendations will be done based on the conclusions of the report.

The major takeaway is that the type and amount of steel used in the process "Steel Core Piles" have the most significant overall environmental impact and thus present the biggest opportunity for lowering it. As the analysis has shown, the amount of steel has significant influence on particular matter formation and human carcinogenic toxicity. It can therefore be recommended to focus on the optimization efforts on the amount of steel used in the process Steel core piles keeping in mind the regulatory and safety standards in construction industry.

As for the amount of steel in steel core piles, the type of steel is also sensitive to freshwater eutrophication and affecting the endpoint ecosystem. Furthermore it affects the impact category ozone formation, which accounts to the endpoint of human health. One of the major takeaways is that the impact category freshwater eutrophication is being affected the most irrespective of the steel type used in the model.

Possible recommendations for reducing the environmental impact of steel used in steel core piles are:

1. The reduction of the amount of steel used. This could be achieved by changing the thickness of the casings used, while maintaining the technical requirements and safety standards.
2. A change in the type of steel used. This could entail using a higher share of recycled steel or steel produced using a more sustainable production process, which uses less energy intensive. However, since the current model assumes steel production based on a European mix of electricity and heat production (most efficient currently), the potential for optimization in this point is questionable.

From the scenario analysis of the type of cement in the unit process soil stabilisation, it was determined that the most impacted category is freshwater eutrophication (Figure 17). It is recommended to use a type of cement which has less impact on freshwater ecotoxicity. The results might change when the actual percentage of type of raw material used in Multicement is implemented in SimaPro, since the material has a lower carbon footprint compared to traditionally produced materials [22].

As the analysis of the sheet pile walls process has shown, neither the amount of steel nor the type of steel used in this process has significant environmental impact. So, it is not a priority to change anything in this respect for this unit process.

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A Appendix

A.1 Life Cycle Inventory

A.1.1 Data representativeness

Table 6: Detailed table of representativeness

Process			Representativeness					Type	Type of Source	Access	Value	Unit process
			Very High	High	Medium	Low	Very low					
Soil stabilization	Columns material	Mass	X					kg	Constractor/Supplier	Direct dialogue	13,079,000.00	-
		Specifications				X		Unit process	Ecoinvent	SimaPro	-	Cement, blast furnace slag 31-50% and 31-50% other alternative constituents {Europe without Switzerland}| market for | Conseq, U
	Machine operation	Type of machine				X		Unit process	Ecoinvent	SimaPro	-	Machine operation, diesel, >= 74.57 kW, high load factor {GLO}| machine operation, diesel, >= 74.57 kW, high load factor | Conseq, U
		Machine hours		X				hr	Contractor/Supplier	Direct dialogue	3,240.00	-
	Transport of material	Mass-Distance		X				tkm	Constractor/Supplier	Direct dialogue	195,789.11	-
		Type of vehicle				X		Unit process	Ecoinvent	SimaPro	-	Transport, Transport of masses market for transport, freight, lorry >32 metric ton, EURO6 | Conseq, U
	Transport of machine	Mass-Distance		X				tkm	Contractor/Supplier	Direct dialogue	60,225.00	-
		Type of vehicle				X		Unit process	Ecoinvent	SimaPro	-	Transport, freight, lorry >32 metric ton, euro6 {RER}| market for transport, freight, lorry >32 metric ton, EURO6 | Conseq, U
Excavation of masses	Machine operation	Type of machine				X		Unit process	Ecoinvent	SimaPro	-	Excavation, hydraulic digger {RER}| processing | Conseq, U
		Excavated volume		X				m3	Contractor/Supplier	Direct dialogue	242,129.56	-
	Transport of excavated masses (TRUCK)	Mass-Distance	X					tkm	Contractor/Supplier	Direct dialogue	23,103,858.99	-
		Type of vehicle			X			MJ/tkm	Ecoinvent	SimaPro and supplier data	-	Transport, freight, lorry >32 metric ton, euro6 {RER}| market for transport, freight, lorry >32 metric ton, EURO6 | Conseq, U
	Transport of excavated masses (SHIP)	Mass-Distance	X					tkm	Contractor/Supplier	Direct dialogue	2,216,940.43	-
		Type of vehicle			X			MJ/tkm	Ecoinvent modified with supplier data	SimaPro and supplier data	-	Transport, barge ship, bulk, 5500t, 80%LF, empty return/GLO Mass
	Transport of machine	Mass-Distance		X				tkm	Contractor/Supplier	Direct dialogue	60,225.00	-
		Type of vehicle				X		MJ/tkm	Ecoinvent	SimaPro	-	Transport, freight, lorry >32 metric ton, euro6 {RER}| market for transport, freight, lorry >32 metric ton, EURO6 | Conseq, U
Sheet pile walls	Sheet pile walls	Amount of Steel		X				kg	Contractor/Supplier	Direct dialogue	1,230,349.46	-
		Specifications				X		Unit process	Ecoinvent	SimaPro	-	Steel (kg), low-alloyed, hot rolled {RER}| production | Conseq, U
	Machine operation	Type of machine				X		Unit process	Ecoinvent	SimaPro	-	Machine operation, diesel, >= 74.57 kW, high load factor {GLO}| machine operation, diesel, >= 74.57 kW, high load factor | Conseq, U
		Machine hours	X					hr	Contractor/Supplier	Direct dialogue	3,528.00	-
	Transport of machine	Mass-Distance		X				tkm	Contractor/Supplier	Direct dialogue	60,225.00	-
		Type of vehicle				X		Unit process	Ecoinvent	SimaPro	-	Transport, freight, lorry >32 metric ton, euro6 {RER}| market for transport, freight, lorry >32 metric ton, EURO6 | Conseq, U
	Transport of materials	Mass-Distance		X				tkm	Contractor/Supplier	Direct dialogue	1,537,936.82	-
		Type of vehicle				X		Unit process	Ecoinvent	SimaPro	-	Transport, freight, lorry 16-32 metric ton, euro6 {RER}| market for transport, freight, lorry 16-32 metric ton, EURO6 | Conseq, U
Steel core piles	Steel core piles	Mass of Steel				X		kg	Based on literature	Online search	4,377,793.41	-
		Specifications				X		Unit process	Ecoinvent	SimaPro	-	Steel, unalloyed {RER}| steel production, converter, unalloyed | Conseq, U
	Machine operation	Type of machine				X		Unit process	Ecoinvent	SimaPro	-	Machine operation, diesel, >= 74.57 kW, high load factor {GLO}| machine operation, diesel, >= 74.57 kW, high load factor | Conseq, U
		Machine hours	X					hr	Own assumption		1,512.00	-
	Transport of materials (CONCRETE)	Mass-Distance				X		tkm	Own assumption		45,778.35	-
		Type of vehicle				X		Unit process	Ecoinvent	SimaPro	-	Transport, freight, lorry >32 metric ton, euro6 {RER}| market for transport, freight, lorry >32 metric ton, EURO6 | Conseq, U
	Volume of Concrete	Volume of mass processed				X		m3	Mixed (EPD, calc, NGI)		1,461.77	-
		Type of material				X		Unit process	Ecoinvent	SimaPro	-	Concrete, normal {CH}| market for | Conseq, U
	Transport of materials (STEEL)	Mass-Distance				X		tkm	Mixed (EPD & assumpt)		5,472,241.76	-
		Type of vehicle				X		Unit process	Ecoinvent	SimaPro	-	Transport, freight, lorry 16-32 metric ton, euro6 {RER}| market for transport, freight, lorry 16-32 metric ton, EURO6 | Conseq, U
	Transport of waste (excavated materials)	Mass-Distance	X					tkm	Contractor/Supplier		113,354.74	-
		Type of vehicle				X		Unit process	Ecoinvent	SimaPro	-	Transport, freight, lorry >32 metric ton, euro6 {RER}| market for transport, freight, lorry >32 metric ton, EURO6 | Conseq, U
	Transport of machines	Mass-Distance			X			tkm	Mixed (NGI, assumpt.)		80,300.00	-
		Type of vehicle				X		Unit process	Ecoinvent	SimaPro	-	Transport, freight, lorry >32 metric ton, euro6 {RER}| market for transport, freight, lorry >32 metric ton, EURO6 | Conseq, U
Anchoring	Anchors, wires, heads, tubes, wailing	Specifications				X		Unit process	Ecoinvent	SimaPro	-	Steel, unalloyed {RER}| steel production, converter, unalloyed | Conseq, U
		Amount of steel	X					kg	Contractor/Supplier		235,461.36	-
	Cement	Specifications				X		Unit process	Ecoinvent	SimaPro	-	Cement, Portland {Europe without Switzerland}| market for | Conseq, U
		Amount of cement	X					kg	Contractor/Supplier		54,308.00	-
	Machine operation	Type of machine				X		Unit process	Ecoinvent	SimaPro	-	Machine operation, diesel, >= 74.57 kW, high load factor {GLO}| machine operation, diesel, >= 74.57 kW, high load factor | Conseq, U
		Machine hours	X					hr	Contractor/Supplier	Direct dialogue	3,528.00	-
	Transport of materials (STEEL)	Mass-Distance		X				tkm	Contractor/Supplier	Direct dialogue	294,326.70	-
		Type of vehicle				X		Unit process	Ecoinvent	SimaPro	-	Transport, freight, lorry 16-32 metric ton, euro6 {RER}| market for transport, freight, lorry 16-32 metric ton, EURO6 | Conseq, U
	Transport of materials (Cement)	Mass-Distance		X				tkm	Contractor/Supplier		776.60	-
		Type of vehicle				X		Unit process	Ecoinvent	SimaPro	-	Transport, freight, lorry >32 metric ton, euro6 {RER}| market for transport, freight, lorry >32 metric ton, EURO6 | Conseq, U
	Transport of machines	Mass-Distance		X				tkm	Contractor/Supplier	Direct dialogue	60,225.00	-
		Type of vehicle				X		Unit process	Ecoinvent	SimaPro	-	Transport, freight, lorry >32 metric ton, euro6 {RER}| market for transport, freight, lorry >32 metric ton, EURO6 | Conseq, U
Ground floor slab	Transport of materials (Cement)	Mass-Distance					X	tkm	Own assumption		167,739.00	-
		Type of vehicle				X		Unit process	Ecoinvent	SimaPro	-	Transport, freight, lorry >32 metric ton, euro6 {RER}| market for transport, freight, lorry >32 metric ton, EURO6 | Conseq, U
	Material lean concrete (Magerbetong)	Volume of mass processed					X	m3	NGI assump. & own assumpt.		1,700.00	-
		Type of material				X		Unit process	Ecoinvent	SimaPro	-	Lean concrete {CH}| market for | Conseq, U
	Material concrete	Volume of mass processed					X	m3	NGI assump. & own assumpt.		3,400.00	-
		Type of material				X		Unit process	Ecoinvent	SimaPro	-	Concrete, normal {CH}| market for | Conseq, U

A.1.2 Unit processes

Table 7: Details of the unit process of soil stabilisation

Outputs to technosphere: Products and co-products	Amount	Unit	Quantity	Allocation
Soil stabilisation	1	p	Amount	100%
Input from nature				
Inputs from technosphere: material/fuels			Distribution	
Cement, blast furnace slag 31-50% and 31-50% other alternative constituents {Europe without Switzerland}| market for | Conseq, U	13079000	kg	Undefined	
Machine operation, diesel, >= 74.57 kW, high load factor {GLO}| machine operation, diesel, >= 74.57 kW, high load factor | Conseq, U	3240	hr	Undefined	
Transport, Transport of masses market for transport, freight, lorry >32 metric ton, EURO6 | Conseq, U	195789.1078	tkm	Undefined	
Transport, freight, lorry >32 metric ton, euro6 {RER}| market for transport, freight, lorry >32 metric ton, EURO6 | Conseq, U	60225	tkm	Undefined	

Table 8: Details of the unit process of Sheet Pile Walls

Outputs to technosphere: Products and co-products	Amount	Unit	Quantity	Allocation
Sheet Pile Walls	1	p	Amount	100%
Input from nature				
Inputs from technosphere: material/fuels			Distribution	
Steel (kg), low-alloyed, hot rolled {RER}| production | Conseq, U	1,230,349.46	kg	Undefined	
Machine operation, diesel, >= 74.57 kW, high load factor {GLO}| machine operation, diesel, >= 74.57 kW, high load factor | Conseq, U	3,528.00	hr	Undefined	
Transport, freight, lorry >32 metric ton, euro6 {RER}| market for transport, freight, lorry >32 metric ton, EURO6 | Conseq, U	60,225.00	tkm	Undefined	
Transport, freight, lorry 16-32 metric ton, euro6 {RER}| market for transport, freight, lorry 16-32 metric ton, EURO6 | Conseq, U	1,537,936.82	tkm	Undefined	

Table 9: Details of the unit process of excavation of masses

Outputs to technosphere: Products and co-products	Amount	Unit	Quantity	Allocation
Excavation of masses	1	p	Amount	100%
Input from nature				
Inputs from technosphere: material/fuels			Distribution	
Excavation, hydraulic digger {RER}| processing | Conseq, U	242,129.56	m3	Undefined	
Transport, freight, lorry >32 metric ton, euro6 {RER}| market for transport, freight, lorry >32 metric ton, EURO6 | Conseq, U	23,103,858.99	tkm	Undefined	
Transport, barge ship, bulk, 5500t, 80%LF, empty return/GLO Mass	2,216,940.43	tkm	Undefined	
Transport, freight, lorry >32 metric ton, euro6 {RER}| market for transport, freight, lorry >32 metric ton, EURO6 | Conseq, U	60,225.00	tkm	Undefined	

Table 10: Details of the unit process of Anchoring

Outputs to technosphere: Products and co-products	Amount	Unit	Quantity	Allocation
Anchoring	1	p	Amount	100%
Input from nature				
Inputs from technosphere: material/fuels			Distribution	
Steel, unalloyed {RER}| steel production, converter, unalloyed | Conseq, U	235,461.36	kg	Undefined	
Cement, Portland {Europe without Switzerland}| market for | Conseq, U	54,308.00	kg	Undefined	
Machine operation, diesel, >= 74.57 kW, high load factor {GLO}| machine operation, diesel, >= 74.57 kW, high load factor | Conseq, U	3,528.00	hr	Undefined	
Transport, freight, lorry 16-32 metric ton, euro6 {RER}| market for transport, freight, lorry 16-32 metric ton, EURO6 | Conseq, U	294,326.70	tkm	Undefined	
Transport, freight, lorry >32 metric ton, euro6 {RER}| market for transport, freight, lorry >32 metric ton, EURO6 | Conseq, U	776.60	tkm	Undefined	
Transport, freight, lorry >32 metric ton, euro6 {RER}| market for transport, freight, lorry >32 metric ton, EURO6 | Conseq, U	60,225.00	tkm	Undefined	

Table 11: Details of the unit process of Steel Core Piles

Outputs to technosphere: Products and co-products	Amount	Unit	Quantity	Allocation
Steel Core Piles	1	p	Amount	100%
Input from nature				
Inputs from technosphere: material/fuels			Distribution	
Steel, unalloyed {RER}| steel production, converter, unalloyed | Conseq, U	4,377,793.41	kg	Undefined	
Machine operation, diesel, >= 74.57 kW, high load factor {GLO}| machine operation, diesel, >= 74.57 kW, high load factor | Conseq, U	1,512.00	hr	Undefined	
Transport, freight, lorry >32 metric ton, euro6 {RER}| market for transport, freight, lorry >32 metric ton, EURO6 | Conseq, U	45,778.35	tkm	Undefined	
Concrete, normal {CH}| market for | Conseq, U	1,461.77	m3	Undefined	
Transport, freight, lorry 16-32 metric ton, euro6 {RER}| market for transport, freight, lorry 16-32 metric ton, EURO6 | Conseq, U	5,472,241.76	tkm	Undefined	
Transport, freight, lorry >32 metric ton, euro6 {RER}| market for transport, freight, lorry >32 metric ton, EURO6 | Conseq, U	113,354.74	tkm	Undefined	
Transport, freight, lorry >32 metric ton, euro6 {RER}| market for transport, freight, lorry >32 metric ton, EURO6 | Conseq, U	80,300.00	tkm	Undefined	

Table 12: Details of the unit process of Ground floor slab

Outputs to technosphere: Products and co-products	Amount	Unit	Quantity	Allocation
Ground Floor Slab	1	p	Amount	100%
Input from nature				
Inputs from technosphere: material/fuels			Distribution	
Transport, freight, lorry >32 metric ton, euro6 {RER}| market for transport, freight, lorry >32 metric ton, EURO6 | Conseq, U	1,230,349.46	tkm	Undefined	
Lean concrete {CH}| market for | Conseq, U	3,528.00	m3	Undefined	
Concrete, normal {CH}| market for | Conseq, U	60,225.00	m3	Undefined	

Table 13: Details of the unit process of the final excavation pit

Outputs to technosphere: Products and co-products	Amount	Unit	Quantity	Allocation
Final Pit	1	p	Amount	100%
Input from nature				
Inputs from technosphere: material/fuels	1	p	Distribution	
Soil stabilisation	1	p	Undefined	
Excavation of masses	1	p	Undefined	
Sheet Pile Walls	1	p	Undefined	
Anchoring	1	p	Undefined	
Steel Core Piles	1	p	Undefined	
Ground floor slab	1	p	Undefined	

A.1.3 Excavation masses input data

Table 14: Waste-mass-contribution from different processes respectively transported by Firing & Thorsen deliveries

NO	*plasseringsadresse*	*Vare*	*Vekt*	
EN	location adresses	goods	weight in kg	Assignment to specific process
	Boreslam fra kalk/cement stabilisering	*UTGÅTT Lettforurenset jord, ordinært avfall*	22,779,030	Excavation
	drilling sludge from lime cement colums	*Lettforurenset jord, inert avfall*	121,700	
		Total Boreslam fra kalk/cement stabilisering	**22,900,730**	
	Boreslam fra stålkjærnepeling	*UTGÅTT Lettforurenset jord, ordinært avfall*	2,447,580	Steel Core Piles
	drilling sludge from Steel Core Piles	*Lettforurenset jord, inert avfall*	809,740	
		Total Boreslam fra stålkjærnepeling	**3,257,320**	
	Forurenset masse klasse 2/3	*UTGÅTT Lettforurenset jord, ordinært avfall*	127,039,180	Excavation
	Contaminated mass class 2/3	*Lettforurenset jord, inert avfall*	119,800	
		Total Forurenset masse klasse 2/3	**127,158,980**	
	Kalkstabilisert leire	*UTGÅTT Lettforurenset jord, ordinært avfall*	-	Excavation
		Lettforurenset jord, inert avfall	318,962,900	
		Total Kalkstabilisert leire	**318,962,900**	
	Rene masser med avfall	*Rene rivemasser*	**181,877,920**	Excavation
	Clean masses with waste			
		Sum of all categories	**654,157,850**	

A.2 Life Cycle Impact Assessment

A.2.1 Midpoint results - Characterized

Table 15: Characterised midpoint impact results for all impact categories and all processes; maximum per impact category is highlighted in bold text

			Processes					
Impact category	Unit	Total	Excavation of Masses	Soil Stabilization	Sheet Pile Wall	Steel Core Piles	Anchoring of Sheet Pile Wall	Ground Floor Slab
Global warming	kg CO2 eq	30608388	2214280.1	6659551	5707102	**13931321**	1314726	781408.6
Stratospheric ozone depletion	kg CFC11 eq	8.359375	1.5470833	1.67353	1.560189	**2.936792**	0.466735	0.175045
Ionizing radiation	kBq Co-60 eq	59321.44	26860.568	**83969.75**	-31502.9	-24193.1	2297.149	1890.071
Ozone formation, Human health	kg NOx eq	70851.83	5604.66365	13201.31	13656.41	**33030.59**	3944.327	1414.533
Fine particulate matter formation	kg PM2.5 eq	40394.57	2510.3267	5067.576	9596.733	**21116.4**	1639.502	464.0293
Ozone formation, Terrestrial ecosystems	kg NOx eq	76179.49	5891.61614	13641.11	14787.31	**36244.01**	4162.988	1452.457
Terrestrial acidification	kg SO2 eq	64561.95	4432.1133	11652.14	13247.17	**31226.8**	2879.537	1124.191
Freshwater eutrophication	kg P eq	11784.69	201.449	1232.24	3298.209	**6563.447**	379.0516	110.294
Marine eutrophication	kg N eq	1052.105	16.9482675	25.53994	386.3799	**574.6192**	32.7135	15.90445
Terrestrial ecotoxicity	kg 1,4-DCB	1.23E+08	**50859535.9**	10538505	21722223	34926721	2585758	2021322
Freshwater ecotoxicity	kg 1,4-DCB	1915506	37548.2908	81875.94	786731.4	**944167.7**	55687.42	9494.953
Marine ecotoxicity	kg 1,4-DCB	2553211	75543.3636	111959.1	1016471	**1261199**	74709.98	13328.47
Human carcinogenic toxicity	kg 1,4-DCB	-2589503	14035.2262	73974.06	**569437.7**	-3089095	-165494	7639.316
Human non-carcinogenic toxicity	kg 1,4-DCB	27043958	1444574.64	2221201	9250083	**13080935**	789991	257173.4
Land use	m2a crop eq	789509.4	166830.545	**310562.8**	75308.96	177599	11271.72	47936.43
Mineral resource scarcity	kg Cu eq	797859.6	4885.27375	49418.21	238788.9	**476022.4**	27214.32	1530.529
Fossil resource scarcity	kg oil eq	6987611	814150.66	1060491	1398596	**3277507**	345861.4	91005.98
Water consumption	m3	132956.5	4079.29718	11080.12	40403.18	**57460.96**	3160.467	16772.48

A.2.2 Midpoint results - Substance contribution per impact category

Table 16: Substance contribution per impact category with a cut-off of 2% except for water consumption, where only the 5 most contributing substances are showed. The table continues in next page.

Human Non Carcenogenic

Substance	Compartment	Unit	Total	Excavation of Masses	Soil Stabilization	Sheet Pile Wall	Steel Core Piles	Anchoring of Sheet Pile Wall	Ground Floor Slab
Total of all compartments		kg 1,4-DCB	27043958	1444574.6	2221200.6	9250083	13080935	789991.05	257173.43
Remaining substances		kg 1,4-DCB	2666453.6	430536.14	225634.35	952883.7	961019.96	66237.093	30142.332
Zinc	Water	kg 1,4-DCB	16743355	736554.11	1306898.3	6332160.1	7758762.7	465906.7	143073.08
Arsenic	Water	kg 1,4-DCB	5309606	174561.31	635160.63	1368845.1	2880768.7	173725.61	76544.57
Vanadium	Water	kg 1,4-DCB	1726352	10012.113	15456.011	408951.09	1221487.8	68408.083	2036.904
Lead	Air	kg 1,4-DCB	598191.24	92910.967	38051.307	187242.96	258895.91	15713.557	5376.5387

Land use

Substance	Compartment	Unit	Total	Excavation of Masses	Soil Stabilization	Sheet Pile Wall	Steel Core Piles	Anchoring of Sheet Pile Wall	Ground Floor Slab
Total of all compartments		m2a crop eq	789509.45	166830.55	310562.82	75308.956	177598.97	11271.72	47936.434
Remaining substances		m2a crop eq	12671.345	720.49032	-9063.7488	1231.7149	7398.8933	73.378525	12310.616
Occupation, traffic area, road network	Raw	m2a crop eq	217564.31	122403.11	20605.345	17307.087	49569.989	3180.2228	4498.5546
Occupation, annual crop	Raw	m2a crop eq	155843.02	451.15305	103957.61	7893.2045	27775.812	2362.3629	13402.871
Occupation, forest, intensive	Raw	m2a crop eq	133727.75	11290.762	129237.33	19073.529	-30538.748	-1941.0268	6605.9019
Occupation, mineral extraction site	Raw	m2a crop eq	79584.102	1968.1238	3967.996	18741.948	49599.19	2809.5835	2497.2606
Occupation, traffic area, rail/road embankment	Raw	m2a crop eq	52529.681	25896.811	7176.4429	4700.7844	12914.049	780.45904	1061.1338
Transformation, from forest, secondary (non-use)	Raw	m2a crop eq	47936.58	158.88883	31950.732	2431.8392	8549.2531	727.15728	4118.7087
Occupation, dump site	Raw	m2a crop eq	43305.061	1990.672	8901.578	-4002.0274	33524.265	1888.8296	1001.7441
Transformation, from forest, primary (non-use)	Raw	m2a crop eq	36702.196	125.28109	24247.316	1929.3798	6716.7704	565.4427	3118.0064
Occupation, industrial area	Raw	m2a crop eq	34470.155	1832.278	6319.6878	7223.4692	16416.23	1196.4233	1482.0661
Occupation, permanent crop	Raw	m2a crop eq	-24824.744	-7.0242037	-16737.472	-1221.9732	-4326.7326	-371.11271	-2160.4291

Mineral Resource Scarcity

Substance	Compartment	Unit	Total	Excavation of Masses	Soil Stabilization	Sheet Pile Wall	Steel Core Piles	Anchoring of Sheet Pile Wall	Ground Floor Slab
Total of all compartments		kg Cu eq	797859.64	4885.2737	49418.209	238788.94	476022.36	27214.323	1530.5287
Remaining substances		kg Cu eq	19871.607	676.84398	3116.908	5871.4985	9087.3448	584.07814	534.93343
Iron	Raw	kg Cu eq	525923.32	3075.1238	3277.3199	118296.75	379563.11	21206.51	504.50961
Nickel	Raw	kg Cu eq	100679.5	777.22079	1352.0969	54797.197	41077.51	2459.3284	216.14611
Molybdenum	Raw	kg Cu eq	99280.386	206.87859	-2645.6592	58333.714	41398.357	2466.2747	-479.17953
Clay, unspecified	Raw	kg Cu eq	52104.828	149.20658	44317.543	1489.7868	4896.0408	498.13151	754.11907

Fossil Resource Scarcity

Substance	Compartment	Unit	Total	Excavation of Masses	Soil Stabilization	Sheet Pile Wall	Steel Core Piles	Anchoring of Sheet Pile Wall	Ground Floor Slab
Total of all compartments		kg oil eq	6987611.3	814150.66	1060490.5	1398596.2	3277506.6	345861.41	91005.977
Remaining substances		kg oil eq	141128.72	22396.833	48197.198	45037.306	20538.064	1638.2431	3321.0773
Coal, hard	Raw	kg oil eq	3547304.5	32283.488	292915.8	756696.29	2309470.8	130407.81	25530.308
Oil, crude	Raw	kg oil eq	2608797	699658.88	637086.43	360975.52	680114.92	187235.85	43725.356
Gas, natural/m3	Raw	kg oil eq	690381.12	59811.454	82291.091	235887.06	267382.77	26579.507	18429.235

Water Consumption

Substance	Compartment	Unit	Total	Excavation of Masses	Soil Stabilization	Sheet Pile Wall	Steel Core Piles	Anchoring of Sheet Pile Wall	Ground Floor Slab
Total of all compartments		m3	132956.5	4079.2972	11080.12	40403.182	57460.956	3160.4675	16772.48
Remaining substances		m3	70659.84	3585.7856	-12645.58	21792.089	49962.159	3142.0516	4823.3349
Water, turbine use, unspecified natural origin, RoW	Raw	m3	34135253	760534.64	1171080.6	15587595	15565236	945496.56	105311.23
Water, turbine use, unspecified natural origin, UA	Raw	m3	2215812.3	66669.811	896080.67	266935.84	920761.35	59240.492	6124.1141
Water, JP	Water	m3	1094041.4	3206.8255	48526.874	315323.05	685519.2	38638.886	2826.5687
Water, turbine use, unspecified natural origin, CH	Raw	m3	1024049.7	137685.09	172051.25	-2483608.4	1612837.2	67981.299	1517103.2
Water, KR	Water	m3	964604.69	-7271.7119	37115.733	321422.54	577064.84	34344.475	1928.8184

Table 17: Substance contribution per impact category with a cut-off of 2%

Global warming

Substance	Compartment	Unit	Total	Excavation of Masses	Soil Stabilization	Sheet Pile Wall	Steel Core Piles	Anchoring of Sheet Pile Wall	Ground Floor Slab
Total of all compartments		kg CO2 eq	30608388	2214280.1	6659550.6	5707101.6	13931321	1314726	781408.56
Remaining substances		kg CO2 eq	506098.82	69980.875	210072.27	56209.801	129422.64	14129.921	26283.309
Carbon dioxide, fossil	Air	kg CO2 eq	27643654	2088146.3	6235684.1	5092224.1	12283545	1206886.6	737167.96
Methane, fossil	Air	kg CO2 eq	2458635.2	56152.97	213794.27	558667.7	1518353.5	93709.426	17957.293

Stratospheric Ozone Depletion

Substance	Compartment	Unit	Total	Excavation of Masses	Soil Stabilization	Sheet Pile Wall	Steel Core Piles	Anchoring of Sheet Pile Wall	Ground Floor Slab
Total of all compartments		kg CFC11 eq	8.3593747	1.5470833	1.6735301	1.5601885	2.9367925	0.466735	0.17504521
Remaining substances		kg CFC11 eq	0.037425349	0.001496821	0.00335615	0.00794891	0.022917268	0.001376282	0.000329919
Dinitrogen monoxide	Air	kg CFC11 eq	5.8207666	1.0556366	1.1959411	1.1083955	2.0091437	0.31065567	0.14099403
Methane, bromotrifluoro-, Halon 1301	Air	kg CFC11 eq	1.7938721	0.47552175	0.42809485	0.25851148	0.47895122	0.12856384	0.024228937
Methane, chlorodifluoro-, HCFC-22	Air	kg CFC11 eq	0.52096108	0.003220838	0.029668762	0.11125194	0.35495689	0.019893222	0.00196943
Methane, bromochlorodifluoro-, Halon 1211	Air	kg CFC11 eq	0.18634952	0.011207327	0.016469229	0.074080733	0.070823358	0.00624598	0.007522894

Ionizing Radiation

Substance	Compartment	Unit	Total	Excavation of Masses	Soil Stabilization	Sheet Pile Wall	Steel Core Piles	Anchoring of Sheet Pile Wall	Ground Floor Slab
Total of all compartments		kBq Co-60 eq	59321.444	26860.568	83969.751	-31502.95	-24193.145	2297.1491	1890.0705
Remaining substances		kBq Co-60 eq	772.43213	10822.62	67613.665	-38443.624	-38425.377	-1858.3181	1063.4655
Carbon-14	Air	kBq Co-60 eq	58549.012	16037.948	16356.086	6940.6742	14232.232	4155.4673	826.60498

Ozone Formation (Human Health)

Substance	Compartment	Unit	Total	Excavation of Masses	Soil Stabilization	Sheet Pile Wall	Steel Core Piles	Anchoring of Sheet Pile Wall	Ground Floor Slab
Total of all compartments		kg NOx eq	70851.832	5604.6636	13201.309	13656.405	33030.593	3944.3274	1414.5333
Remaining substances		kg NOx eq	288.0586	21.990047	44.035881	59.583386	144.33222	13.853431	4.2636367
Nitrogen oxides	Air	kg NOx eq	62121.301	5123.931	12481.352	11805.591	27771.534	3586.4763	1352.4169
NMVOC	Air	kg NOx eq	8442.4725	458.74264	675.92172	1791.231	5114.7267	343.99771	57.852772

Fine Particulate Matter

Substance	Compartment	Unit	Total	Excavation of Masses	Soil Stabilization	Sheet Pile Wall	Steel Core Piles	Anchoring of Sheet Pile Wall	Ground Floor Slab
Total of all compartments		kg PM2.5 eq	40394.568	2510.3267	5067.5764	9596.7326	21116.4	1639.5025	464.02926
Remaining substances		kg PM2.5 eq	330.58989	11.272461	67.985441	57.687235	174.15024	11.417966	8.0765457
Particulates, <2.5 um	Air	kg PM2.5 eq	21708.424	1207.4205	1709.5451	5752.9273	12100.033	797.19389	141.30485
Sulfur dioxide	Air	kg PM2.5 eq	11522.21	728.00133	1917.0972	2487.5031	5787.3485	436.37822	165.88201
Nitrogen oxides	Air	kg PM2.5 eq	6833.3431	563.63241	1372.9487	1298.615	3054.8688	394.51239	148.76586

Ozone formation (TE)

Substance	Compartment	Unit	Total	Excavation of Masses	Soil Stabilization	Sheet Pile Wall	Steel Core Piles	Anchoring of Sheet Pile Wall	Ground Floor Slab
Total of all compartments		kg NOx eq	76179.493	5891.6161	13641.112	14787.315	36244.006	4162.9876	1452.4574
Remaining substances		kg NOx eq	456.43117	28.599812	70.775307	95.851606	232.07836	22.292762	6.8333262
Nitrogen oxides	Air	kg NOx eq	62121.301	5123.931	12481.352	11805.591	27771.534	3586.4763	1352.4169
NMVOC	Air	kg NOx eq	13601.761	739.08536	1088.985	2885.8721	8240.393	554.21853	93.207244

Terrestial Acidification

Substance	Compartment	Unit	Total	Excavation of Masses	Soil Stabilization	Sheet Pile Wall	Steel Core Piles	Anchoring of Sheet Pile Wall	Ground Floor Slab
Total of all compartments		kg SO2 eq	64561.951	4432.1133	11652.143	13247.17	31226.797	2879.5368	1124.1913
Remaining substances		kg SO2 eq	170.27512	10.563099	5.1468179	37.70212	109.37523	7.0160919	0.47176297
Sulfur dioxide	Air	kg SO2 eq	39731.76	2510.3494	6610.68	8577.5968	19956.374	1504.7525	572.00693
Nitrogen oxides	Air	kg SO2 eq	22363.668	1844.6151	4493.2866	4250.0127	9997.7524	1291.1315	486.87007
Ammonia	Air	kg SO2 eq	2296.2481	66.585631	543.02983	381.85854	1163.2948	76.636783	64.842544

Freshwater Eutrophication

Substance	Compartment	Unit	Total	Excavation of Masses	Soil Stabilization	Sheet Pile Wall	Steel Core Piles	Anchoring of Sheet Pile Wall	Ground Floor Slab
Total of all compartments		kg P eq	11784.69	201.449	1232.2396	3298.2086	6563.4469	379.05159	110.29399
Remaining substances		kg P eq	41.916053	0.49237958	23.688231	2.9635832	11.074189	0.84836381	2.8493062
Phosphate	Water	kg P eq	11742.774	200.95662	1208.5513	3295.245	6552.3727	378.20323	107.44469

Marine Eutrophication

Substance	Compartment	Unit	Total	Excavation of Masses	Soil Stabilization	Sheet Pile Wall	Steel Core Piles	Anchoring of Sheet Pile Wall	Ground Floor Slab
Total of all compartments		kg N eq	1052.1052	16.948268	25.539941	386.3799	574.61918	32.713496	15.904447
Remaining substances		kg N eq	5.6219974	0.093588853	0.064169435	2.5457576	2.748853	0.15975942	0.009869105
Nitrate	Water	kg N eq	753.51113	13.282423	21.026913	252.99945	426.89616	23.96722	15.338964
Ammonium, ion	Water	kg N eq	263.50564	2.7832348	3.952117	115.73927	132.69145	7.8307581	0.50881094
Nitrogen, organic bound	Water	kg N eq	29.466462	0.78902089	0.49674148	15.095423	12.282715	0.75575824	0.046803258

Terrestial Ecotoxicity

Substance	Compartment	Unit	Total	Excavation of Masses	Soil Stabilization	Sheet Pile Wall	Steel Core Piles	Anchoring of Sheet Pile Wall	Ground Floor Slab
Total of all compartments		kg 1,4-DCB	1.23E+08	50859536	10538505	21722223	34926721	2585757.8	2021322.5
Remaining substances		kg 1,4-DCB	4776518.4	553944.54	560512.19	1641571.7	1847544.1	119928.16	53017.79
Copper	Air	kg 1,4-DCB	81475988	35017829	6715972.8	13903781	22777900	1681931.2	1378575
Antimony	Air	kg 1,4-DCB	21927419	12456263	1880129	1616271.4	5221476.5	316674.98	436604.53
Zinc	Air	kg 1,4-DCB	8668448.3	1909195.2	601591.47	3116551.8	2756969.9	187254.28	96885.709
Nickel	Air	kg 1,4-DCB	3230765.2	344001.37	339213.6	980555.61	1405297.5	135012.68	26684.428
Vanadium	Air	kg 1,4-DCB	2574925.3	578303.4	441085.77	463491.67	917533	144956.49	29555.015

Freshwater Ecotoxicity

Substance	Compartment	Unit	Total	Excavation of Masses	Soil Stabilization	Sheet Pile Wall	Steel Core Piles	Anchoring of Sheet Pile Wall	Ground Floor Slab
Total of all compartments		kg 1,4-DCB	1915505.8	37548.291	81875.937	786731.44	944167.74	55687.42	9494.9533
Remaining substances		kg 1,4-DCB	27210.211	2808.9246	4051.9516	28716.896	-8602.2843	-261.29697	496.02078
Copper	Water	kg 1,4-DCB	881870.73	11845.135	35085.676	446456.75	362230.1	21964.721	4288.3483
Vanadium	Water	kg 1,4-DCB	507918.41	2945.6907	4547.3883	120319.5	359379.87	20126.676	599.28746
Zinc	Water	kg 1,4-DCB	428669.72	18849.864	33446.381	162127.78	198659.3	11924.273	3662.1205
Nickel	Water	kg 1,4-DCB	69836.711	1098.6759	4744.5407	29110.517	32500.753	1933.0467	449.17624

Marine Ecotoxicity

Substance	Compartment	Unit	Total	Excavation of Masses	Soil Stabilization	Sheet Pile Wall	Steel Core Piles	Anchoring of Sheet Pile Wall	Ground Floor Slab
Total of all compartments		kg 1,4-DCB	2553211.3	75543.364	111959.08	1016471.5	1261198.9	74709.978	13328.467
Remaining substances		kg 1,4-DCB	87576.402	29154.053	9833.3666	47750.32	-1286.321	532.33112	1592.6522
Copper	Water	kg 1,4-DCB	1049549.2	13729.74	41655.386	531773.71	431162.2	26146.635	5081.5631
Vanadium	Water	kg 1,4-DCB	719076.39	4171.1977	6437.8756	170339.96	508784.98	28493.945	848.42943
Zinc	Water	kg 1,4-DCB	610374.01	27143.172	48150.245	230478.26	282214.06	17138.649	5249.6183
Nickel	Water	kg 1,4-DCB	86635.269	1345.2016	5882.2111	36129.233	40324.002	2398.4181	556.20409

Human Carcenogenic

Substance	Compartment	Unit	Total	Excavation of Masses	Soil Stabilization	Sheet Pile Wall	Steel Core Piles	Anchoring of Sheet Pile Wall	Ground Floor Slab
Total of all compartments		kg 1,4-DCB	-2589502.8	14035.226	73974.062	569437.71	-3089095.1	-165494.02	7639.3161
Remaining substances		kg 1,4-DCB	83659.883	2872.0764	9389.5582	27414.471	39734.993	3382.7942	865.99005
Chromium VI	Water	kg 1,4-DCB	-2673162.7	11163.15	64584.504	542023.24	-3128830.1	-168876.81	6773.3261

A.2.3 Midpoint results - Normalized

Table 18: Normalized midpoint impact results for all impact categories and all processes; maximum per impact category is highlighted in bold text

		Processes					
Impact category	Total	Excavation of Masses	Soil Stabilization	Sheet Pile Wall	Steel Core Piles	Anchoring of Sheet Pile Wall	Ground Floor Slab
Global warming	3832.17	277.2279	833.7757	714.5291	**1744.201**	164.6037	97.83235
Stratospheric ozone depletion	139.6016	25.83629	27.94795	26.05515	**49.04443**	7.794474	2.923255
Ionizing radiation	123.3886	55.86998	**174.6571**	-65.5261	-50.32174	4.77807	3.931347
Ozone formation, Human health	3443.399	272.3867	641.5836	663.7013	**1605.287**	191.6943	68.74632
Fine particulate matter formation	1579.428	98.15377	198.1422	375.2322	**825.6513**	64.10455	18.14354
Ozone formation, Terrestrial ecosystems	4288.905	331.698	767.9946	832.5258	**2040.538**	234.3762	81.77335
Terrestrial acidification	1575.312	108.1436	284.3123	323.231	**761.9338**	70.2607	27.43027
Freshwater eutrophication	18148.42	310.2315	1897.649	5079.241	**10107.71**	583.7395	169.8528
Marine eutrophication	228.3068	3.677774	5.542167	83.84444	**124.6924**	7.098829	3.451265
Terrestrial ecotoxicity	8070.637	**3346.557**	693.4336	1429.322	2298.178	170.1429	133.003
Freshwater ecotoxicity	76045.58	1490.667	3250.475	31233.24	**37483.46**	2210.791	376.9496
Marine ecotoxicity	58723.86	1737.497	2575.059	23378.84	**29007.58**	1718.329	306.5547
Human carcinogenic toxicity	-251440.7	1362.82	7182.881	**55292.4**	-299951.1	-16069.5	741.7776
Human non-carcinogenic toxicity	865.4066	46.22639	71.07842	296.0027	**418.5899**	25.27971	8.22955
Land use	127.9005	27.02655	**50.31118**	12.20005	28.77103	1.826019	7.765702
Mineral resource scarcity	6.646171	0.040694	0.411654	1.989112	**3.965266**	0.226695	0.012749
Fossil resource scarcity	7127.364	830.4337	1081.7	1426.568	**3343.057**	352.7786	92.8261
Water consumption	498.5869	15.29736	41.55045	151.5119	**215.4786**	11.85175	62.8968

A.2.4 Midpoint results - weighted

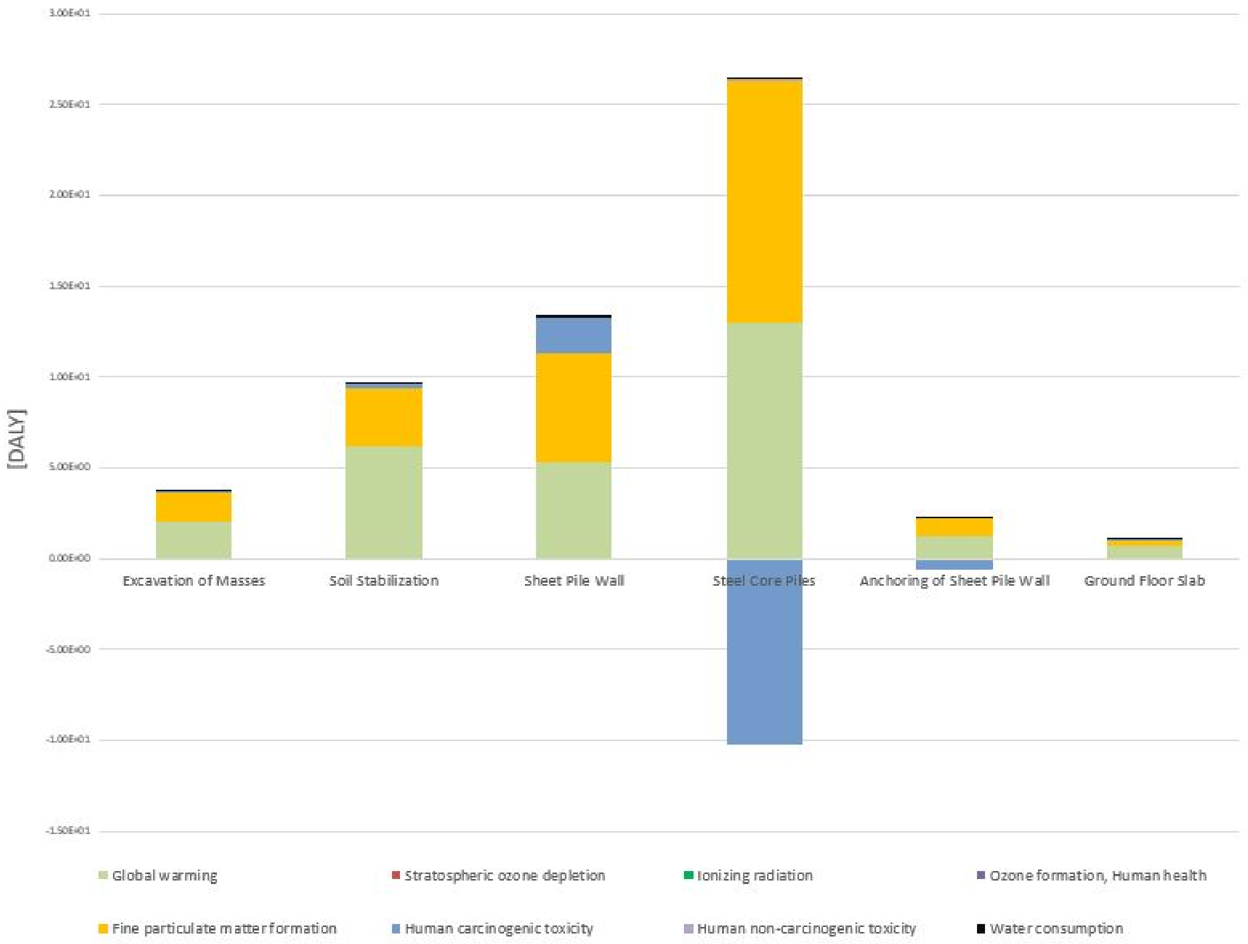

Figure 22: Weighted midpoint results for Human health [DALY]

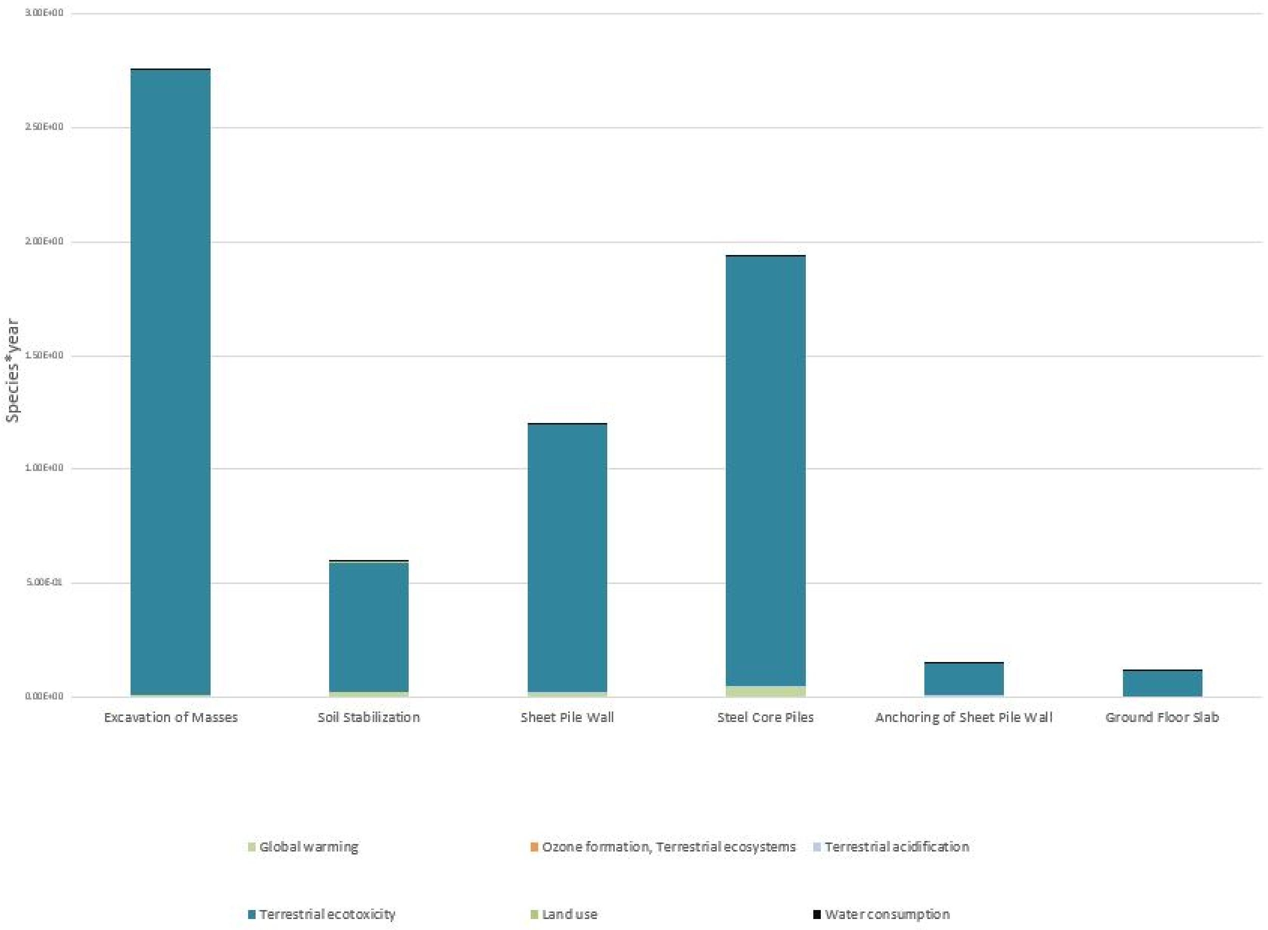

Figure 23: Weighted midpoint results for terrestrial ecosystem [species*yr]

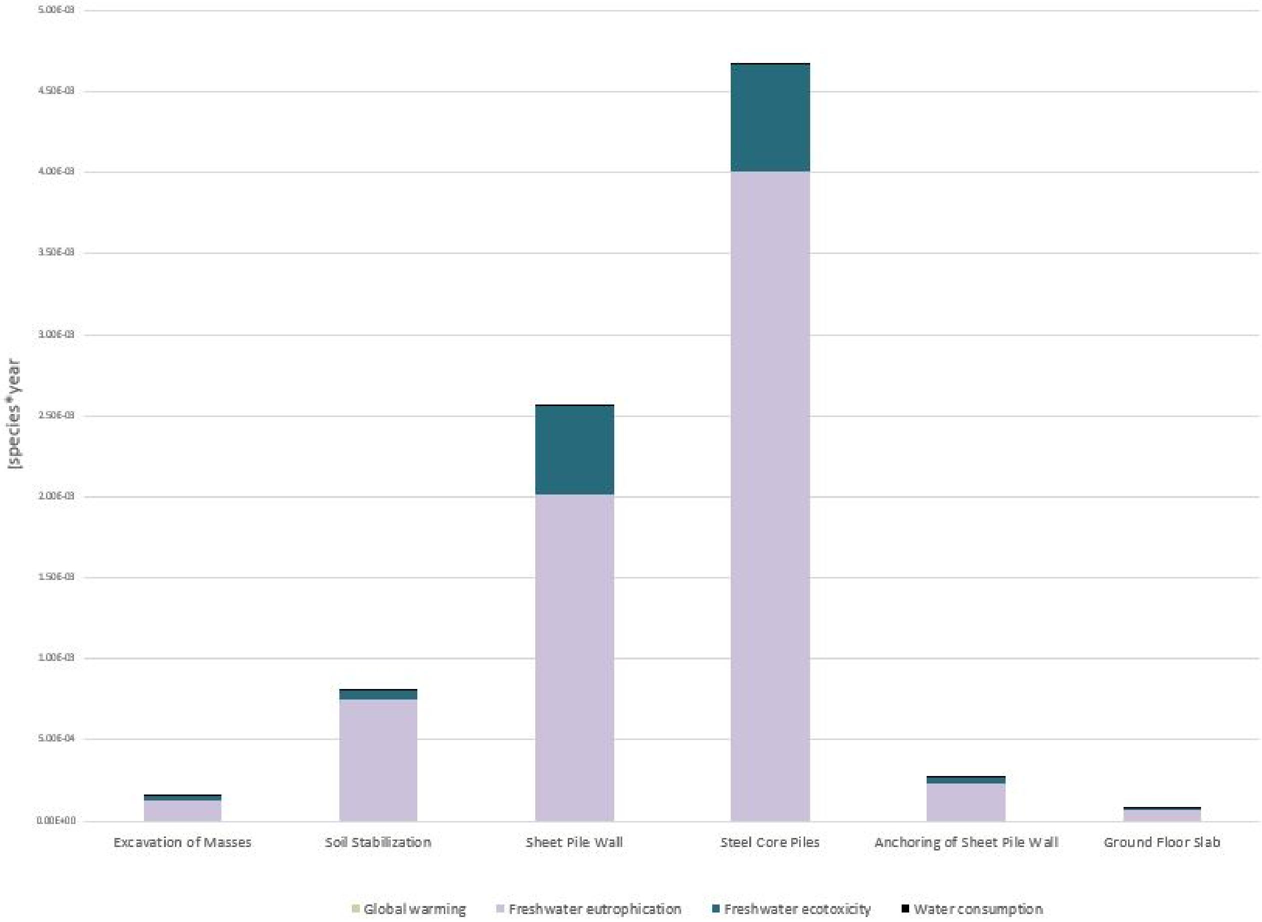

Figure 24: Weighted midpoint results for freshwater ecosystem [species*yr]

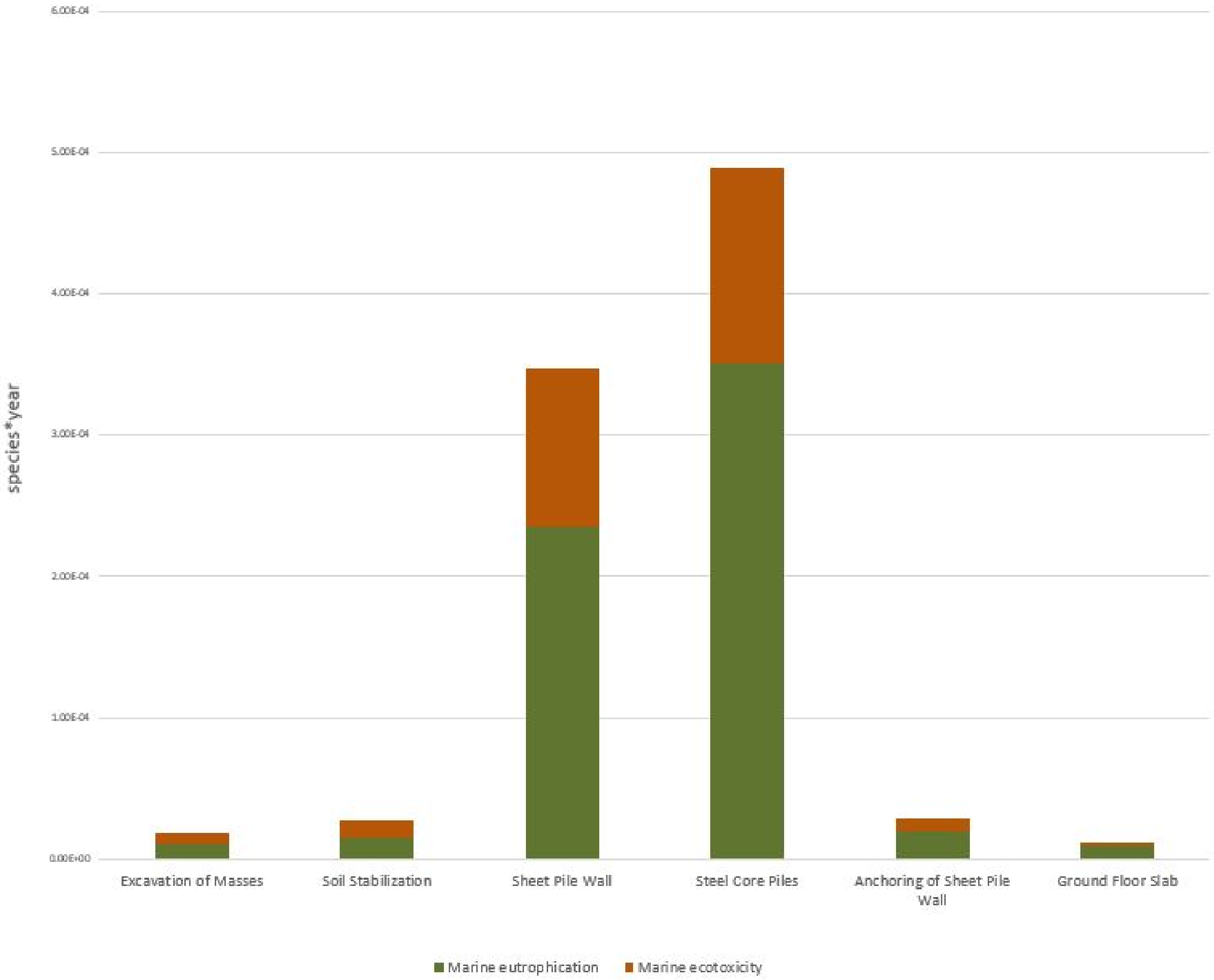

Figure 25: Weighted midpoint results for marine ecosystem [species*yr]

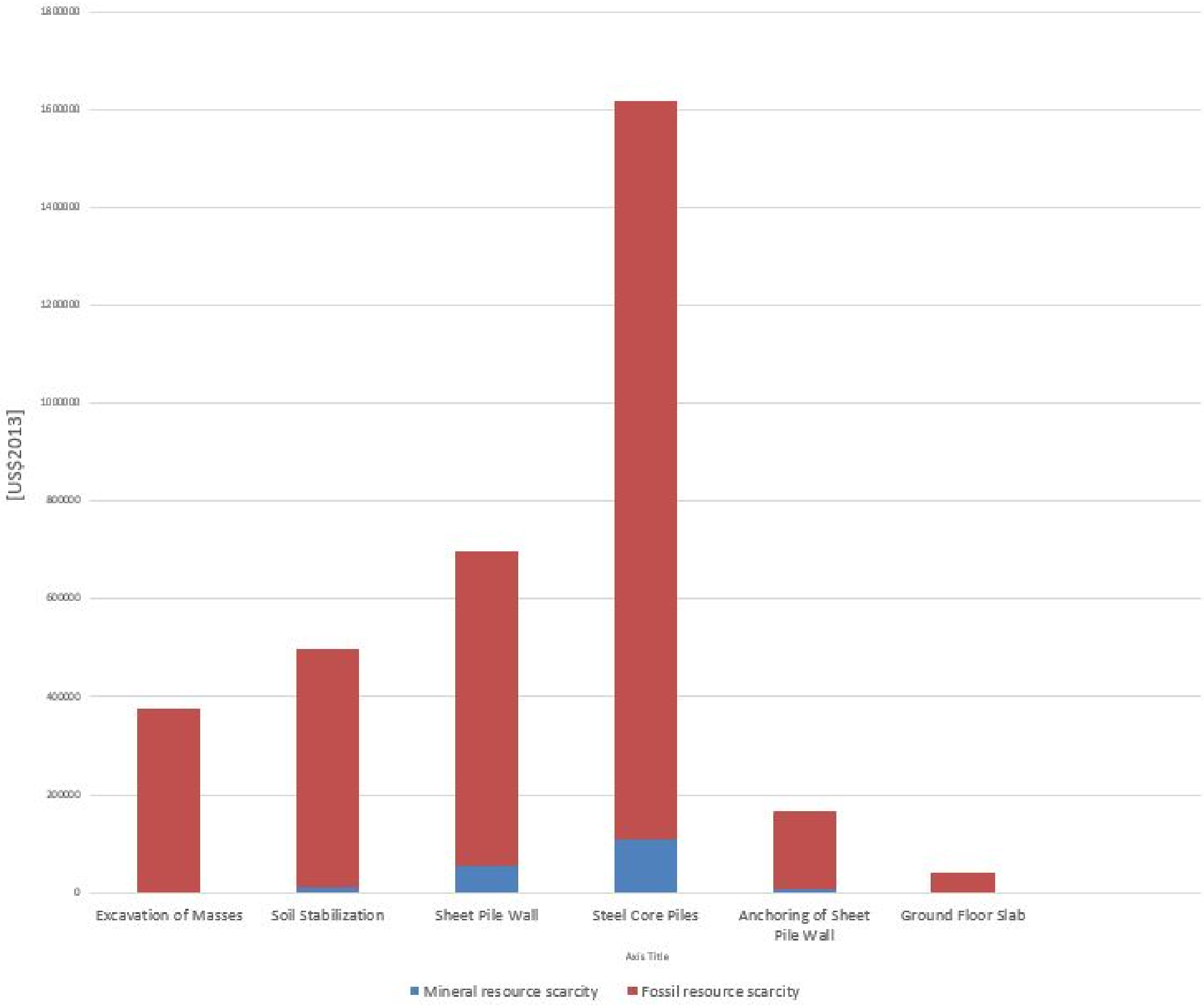

Figure 26: Weighted midpoint results for resource scarcity [US$2013]

A.2.5 Endpoint results - Characterized

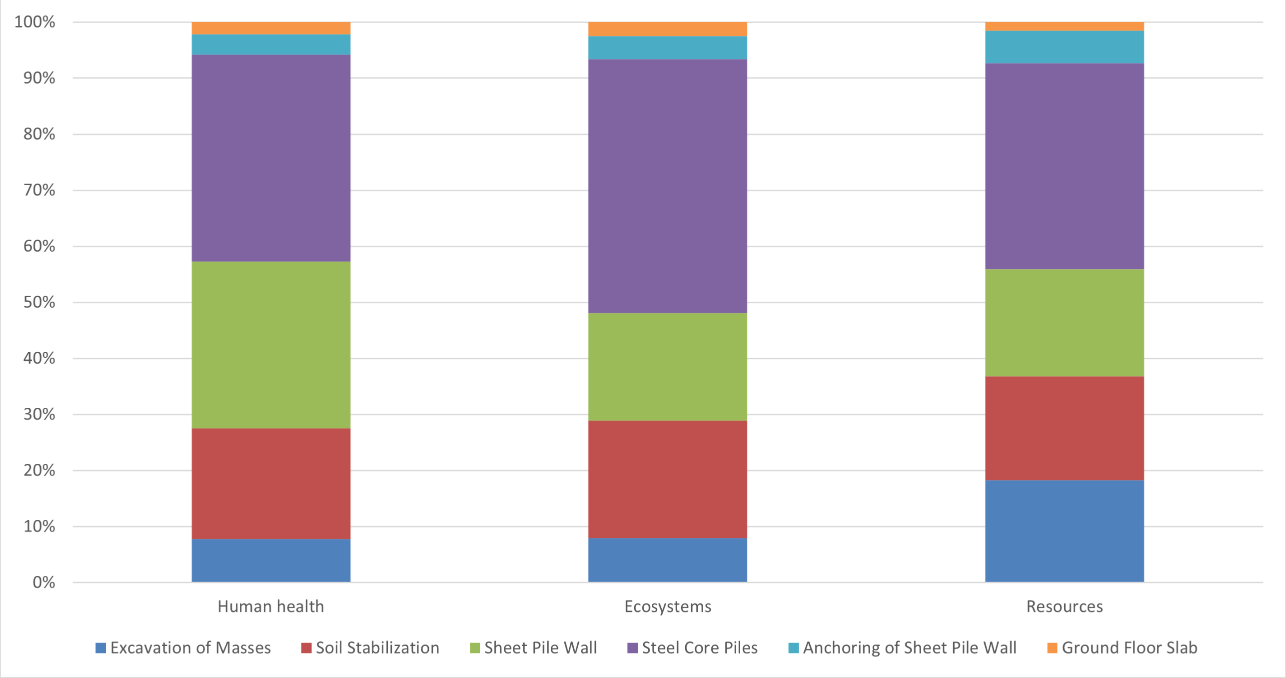

Figure 27: Process contribution for the endpoint results for the three impact categories, as well as the six analysed processes

Table 19: Endpoint results characterized; all single values

Impact category	Unit	Total	Excavation of Masses	Soil Stabilization	Sheet Pile Wall	Steel Core Piles	Anchoring of Sheet Pile Wall	Ground Floor Slab
Global warming, Human health	DALY	28.404192	2.05E+00	6.18E+00	5.30E+00	1.29E+01	1.22E+00	7.25E-01
Global warming, Terrestrial ecosystems	species.yr	0.0857168	6.20E-03	1.86E-02	1.60E-02	3.90E-02	3.68E-03	2.19E-03
Global warming, Freshwater ecosystems	species.yr	2.341E-06	1.69E-07	5.09E-07	4.37E-07	1.07E-06	1.01E-07	5.98E-08
Stratospheric ozone depletion	DALY	0.0044361	8.21E-04	8.88E-04	8.28E-04	1.56E-03	2.48E-04	9.29E-05
Ionizing radiation	DALY	0.0005045	2.28E-04	7.13E-04	-2.67E-04	-2.05E-04	1.96E-05	1.61E-05
Ozone formation, Human health	DALY	0.0644845	5.10E-03	1.20E-02	1.24E-02	3.01E-02	3.59E-03	1.29E-03
Fine particulate matter formation	DALY	25.392498	1.58E+00	3.18E+00	6.03E+00	1.33E+01	1.03E+00	2.92E-01
Ozone formation, Terrestrial ecosystems	species.yr	0.0098267	7.60E-04	1.76E-03	1.91E-03	4.68E-03	5.37E-04	1.87E-04
Terrestrial acidification	species.yr	0.0136865	9.40E-04	2.47E-03	2.81E-03	6.62E-03	6.10E-04	2.38E-04
Freshwater eutrophication	species.yr	0.0078922	1.35E-04	8.25E-04	2.21E-03	4.40E-03	2.54E-04	7.39E-05
Marine eutrophication	species.yr	1.789E-06	2.88E-08	4.34E-08	6.57E-07	9.77E-07	5.56E-08	2.70E-08
Terrestrial ecotoxicity	species.yr	0.0013983	5.80E-04	1.20E-04	2.48E-04	3.98E-04	2.95E-05	2.30E-05
Freshwater ecotoxicity	species.yr	0.0013276	2.60E-05	5.67E-05	5.45E-04	6.55E-04	3.86E-05	6.57E-06
Marine ecotoxicity	species.yr	0.0002684	7.93E-06	1.18E-05	1.07E-04	1.33E-04	7.85E-06	1.40E-06
Human carcinogenic toxicity	DALY	-8.597026	4.66E-02	2.46E-01	1.89E+00	-1.03E+01	-5.49E-01	2.54E-02
Human non-carcinogenic toxicity	DALY	6.167059	3.29E-01	5.06E-01	2.11E+00	2.98E+00	1.80E-01	5.86E-02
Land use	species.yr	0.0070056	1.48E-03	2.75E-03	6.68E-04	1.58E-03	1.00E-04	4.25E-04
Mineral resource scarcity	USD2013	184384.38	1.13E+03	1.14E+04	5.52E+04	1.10E+05	6.29E+03	3.54E+02
Fossil resource scarcity	USD2013	1732852.8	3.49E+05	3.44E+05	3.11E+05	5.94E+05	1.06E+05	2.87E+04
Water consumption, Human health	DALY	-0.006274	3.85E-03	8.54E-03	-3.79E-02	1.80E-02	9.98E-04	2.90E-04
Water consumption, Terrestrial ecosystem	species.yr	0.0006073	3.16E-05	8.66E-05	8.47E-05	3.67E-04	2.17E-05	1.55E-05
Water consumption, Aquatic ecosystems	species.yr	2.153E-07	3.68E-09	-5.64E-09	9.96E-08	1.11E-07	6.60E-09	3.03E-10

A.2.6 Endpoint results - Normalized

Table 20: Normalised endpoint impact results for all impact categories and all processes; maximum per impact category is highlighted in bold text

	Process					
Damage category	Excavation of Masses	Soil Stabilization	Sheet Pile Wall	Steel Core Piles	Anchoring of Sheet Pile Wall	Ground Floor Slab
Human health	167.5866	422.8008	638.1855	**791.4218**	78.65777	45.97324
Ecosystems	6.868769	18.07172	16.60326	**39.09847**	3.569893	2.135868
Resources	12.5009	12.70443	13.0701	**25.13695**	3.997223	1.035773

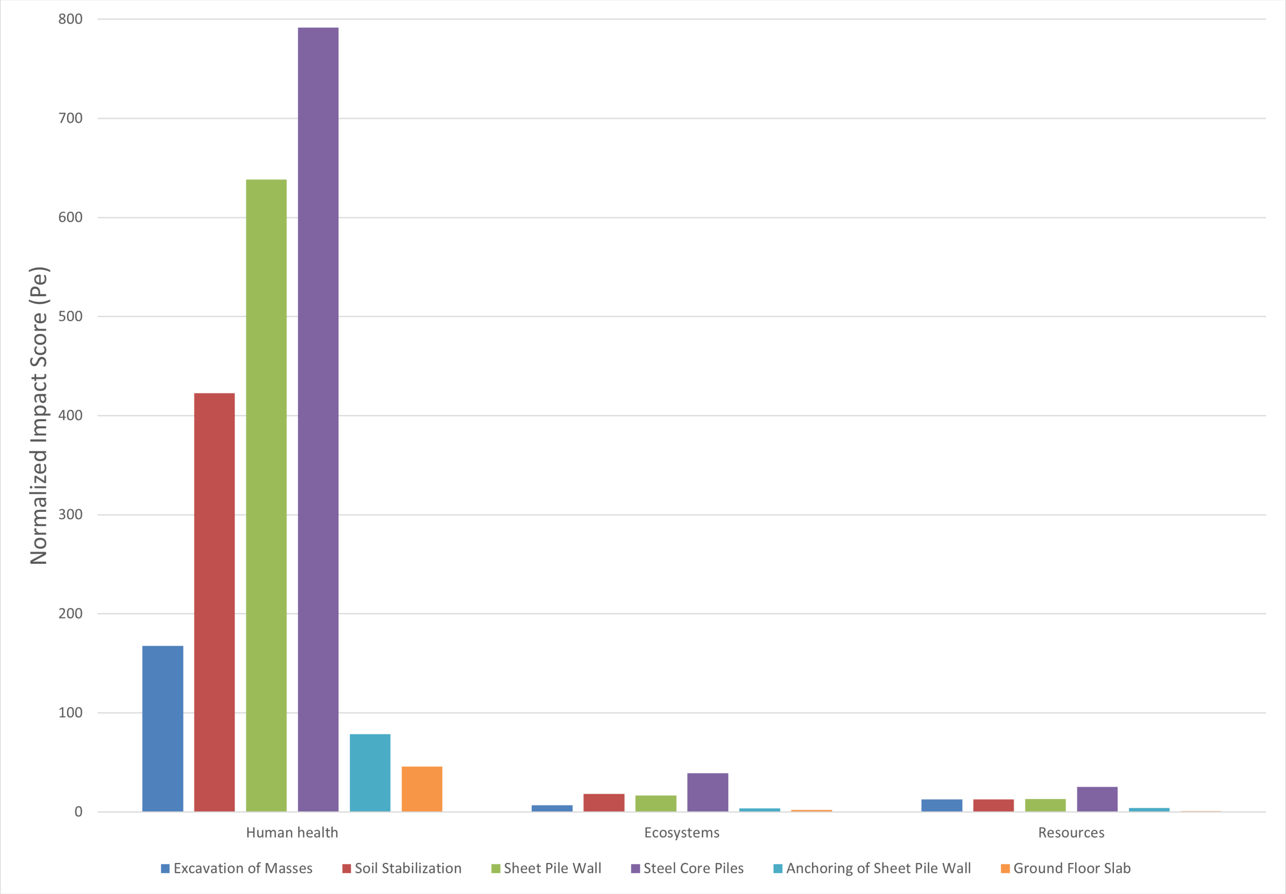

Figure 28: Normalized endpoint results in Person equivalent for the EU 2000, for all three endpoint impact categories

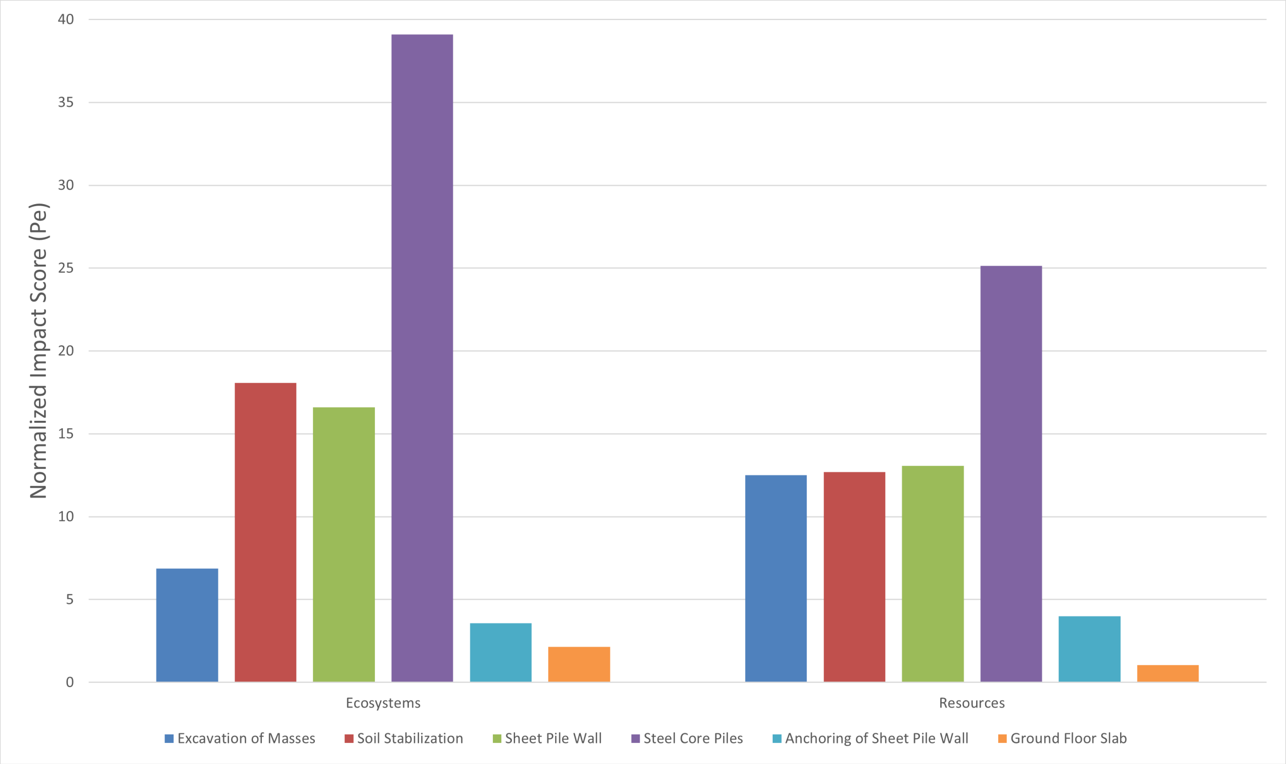

Figure 29: Normalized endpoint results in Person equivalent for the EU 2000, for the two endpoint impact categories ecosystems and resources

A.2.7 Endpoint results - Weighted normalisation

Table 21: Weighted normalised Endpoint impact results for all impact categories and all processes; maximum per impact category is highlighted in bold text

		Process					
Damage category	Excavation of Masses	Soil Stabilization	Sheet Pile Wall	Steel Core Piles	Anchoring of Sheet Pile Wall	Ground Floor Slab	Total
Human health	67034.64	169120.33	255274.22	**316568.72**	31463.11	18389.23	857850.31
Ecosystems	2747.51	7228.69	6641.30	**15639.39**	1427.96	854.35	34539.19
Resources	2500.18	2540.89	2614.02	**5027.39**	799.45	207.15	13689.07
Total	72282.33	178889.90	264529.54	**337235.50**	33690.51	19450.80	906078.58

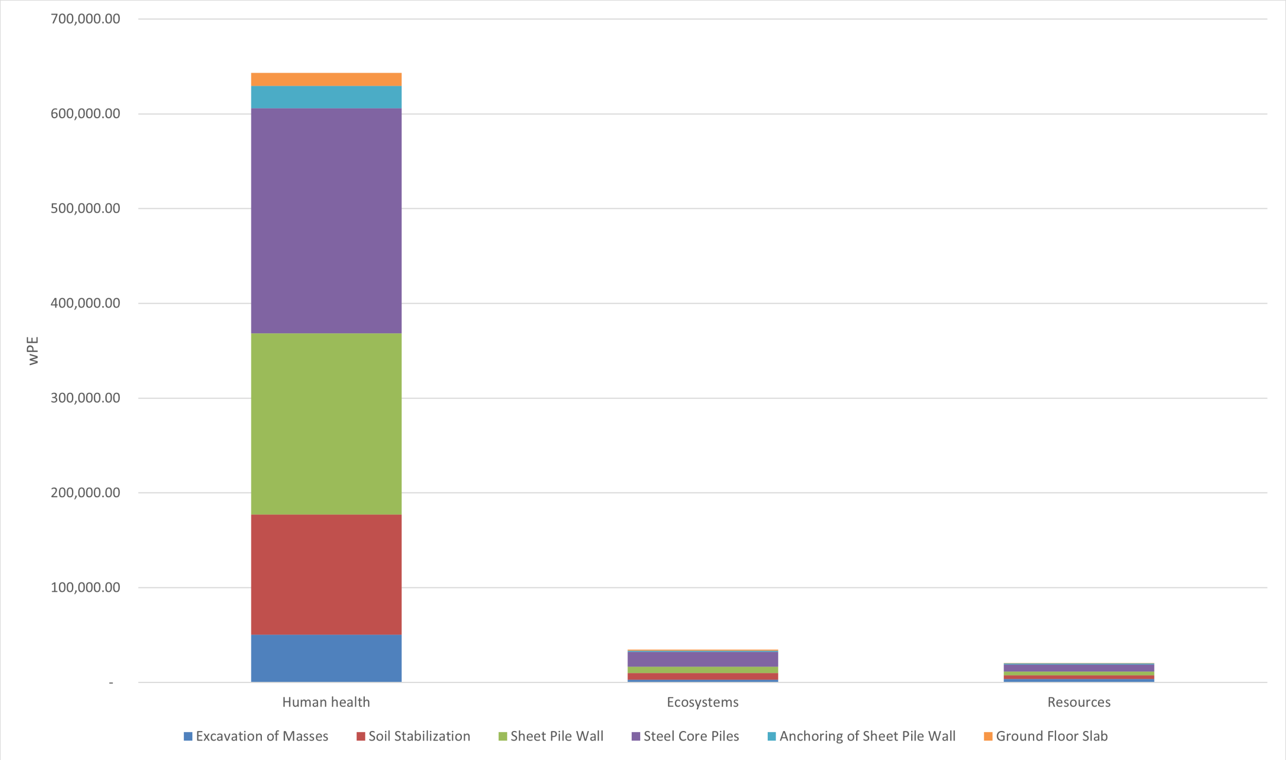

Figure 30: Weighted normalized results per endpoint impact category, with contribution of each process

A.3 Interpretation

A.3.1 Perturbation Analysis

Table 22: Normalized Sensitivity Coefficient (NSC) for all input and midpoint category. The average NSC is calculated using absolute values. In red, values above the threshold of 0.3 for the average or 0.5 for one impact category are indicated, those in green are for the negative threshold. Indicated in yellow are the 3 input for which the NSC of at least one impact category or the average is above the threshold

Process	Soil Stabilization				Excavation of Masses			
Parameter **Impact Category**	**Machine operation**	**Cement**	**Transport of machines**	**Transport of material**	**Transport of masses (SHIP)**	**Machine operation**	**Transport of machines**	**Transport of masses (TRUCK)**
Fine particulate matter formation	0.02	0.11	0.00	0.00	0.00	0.01	0.00	0.05
Fossil resource scarcity	0.05	0.10	0.00	0.00	0.00	0.01	0.00	0.11
Freshwater ecotoxicity	0.00	0.04	0.00	0.00	0.00	0.00	0.00	0.02
Freshwater eutrophication	0.00	0.10	0.00	0.00	0.00	0.00	0.00	0.02
Global warming	0.02	0.20	0.00	0.00	0.00	0.00	0.00	0.07
Human carcinogenic toxicity	0.00	-0.03	0.00	0.00	0.00	0.00	0.00	-0.01
Human non-carcinogenic toxicity	0.00	0.08	0.00	0.00	0.00	0.00	0.00	0.05
Ionizing radiation	0.13	1.28	0.00	0.00	0.00	0.01	0.00	0.44
Land use	0.00	0.39	0.00	0.00	0.00	0.00	0.00	0.21
Marine ecotoxicity	0.00	0.04	0.00	0.00	0.00	0.00	0.00	0.03
Marine eutrophication	0.00	0.02	0.00	0.00	0.00	0.00	0.00	0.02
Mineral resource scarcity	0.00	0.06	0.00	0.00	0.00	0.00	0.00	0.01
Ozone formation, Human health	0.03	0.15	0.00	0.00	0.00	0.02	0.00	0.06
Ozone formation, Terrestrial ecosystems	0.03	0.15	0.00	0.00	0.00	0.02	0.00	0.06
Stratospheric ozone depletion	0.05	0.15	0.00	0.00	0.00	0.01	0.00	0.18
Terrestrial acidification	0.03	0.15	0.00	0.00	0.00	0.01	0.00	0.06
Terrestrial ecotoxicity	0.01	0.07	0.00	0.00	0.00	0.00	0.00	0.41
Water consumption	0.00	0.08	0.00	0.00	0.00	0.00	0.00	0.03
Average NSC over impact categories	0.02	0.18	0.00	0.00	0.00	0.01	0.00	0.10

Process	Sheet Pile Wall				Anchoring of Sheet Pile Wall					
Parameter **Impact Category**	**Machine operation**	**Transport of material steel**	**transport of machines**	**Material steel**	**Machine operation**	**Transport of machines**	**Material steel**	**Trransport of material steel**	**Material cement**	**transportof material cement**
Fine particulate matter formation	0.01	0.01	0.00	0.22	0.01	0.00	0.03	0.00	0.00	0.00
Fossil resource scarcity	0.02	0.01	0.00	0.16	0.02	0.00	0.02	0.00	0.00	0.00
Freshwater ecotoxicity	0.00	0.00	0.00	0.41	0.00	0.00	0.03	0.00	0.00	0.00
Freshwater eutrophication	0.00	0.00	0.00	0.28	0.00	0.00	0.03	0.00	0.00	0.00
Global warming	0.02	0.01	0.00	0.16	0.02	0.00	0.02	0.00	0.00	0.00
Human carcinogenic toxicity	0.00	0.00	0.00	-0.22	0.00	0.00	0.06	0.00	0.00	0.00
Human non-carcinogenic toxicity	0.00	0.01	0.00	0.33	0.00	0.00	0.02	0.00	0.00	0.00
Ionizing radiation	0.05	0.05	0.00	-0.63	0.05	0.00	-0.03	0.01	0.01	0.00
Land use	0.00	0.02	0.00	0.08	0.00	0.00	0.01	0.00	0.00	0.00
Marine ecotoxicity	0.00	0.00	0.00	0.39	0.00	0.00	0.03	0.00	0.00	0.00
Marine eutrophication	0.00	0.00	0.00	0.36	0.00	0.00	0.03	0.00	0.00	0.00
Mineral resource scarcity	0.00	0.00	0.00	0.30	0.00	0.00	0.03	0.00	0.00	0.00
Ozone formation, Human health	0.03	0.01	0.00	0.16	0.03	0.00	0.02	0.00	0.00	0.00
Ozone formation, Terrestrial ecosystems	0.03	0.01	0.00	0.16	0.03	0.00	0.02	0.00	0.00	0.00
Stratospheric ozone depletion	0.04	0.02	0.00	0.13	0.04	0.00	0.01	0.00	0.00	0.00
Terrestrial acidification	0.02	0.01	0.00	0.18	0.02	0.00	0.02	0.00	0.00	0.00
Terrestrial ecotoxicity	0.00	0.04	0.00	0.13	0.00	0.00	0.01	0.01	0.00	0.00
Water consumption	0.00	0.00	0.00	0.30	0.00	0.00	0.02	0.00	0.00	0.00
Average NSC over impact categories	0.01	0.01	0.00	0.26	0.01	0.00	0.03	0.00	0.00	0.00

Process	Steel core Piles							Ground Floor Slab		
Parameter **Impact Category**	**Transport of excavated masses**	**Transport of material steel**	**Transport of machines**	**Machine operation**	**Material concrete**	**Transport of material concrete**	**Material steel**	**Material concrete**	**Transport of concrete**	**Material lean concrete**
Fine particulate matter formation	0.00	0.02	0.00	0.01	0.00	0.00	0.49	0.01	0.00	0.00
Fossil resource scarcity	0.00	0.05	0.00	0.01	0.00	0.00	0.41	0.01	0.00	0.00
Freshwater ecotoxicity	0.00	0.01	0.00	0.00	0.00	0.00	0.48	0.00	0.00	0.00
Freshwater eutrophication	0.00	0.01	0.00	0.00	0.00	0.00	0.55	0.01	0.00	0.00
Global warming	0.00	0.03	0.00	0.01	0.01	0.00	0.41	0.02	0.00	0.01
Human carcinogenic toxicity	0.00	0.00	0.00	0.00	0.00	0.00	1.20	0.00	0.00	0.00
Human non-carcinogenic toxicity	0.00	0.02	0.00	0.00	0.00	0.00	0.45	0.01	0.00	0.00
Ionizing radiation	0.00	0.17	0.00	0.02	0.01	0.00	-0.61	0.02	0.00	0.01
Land use	0.00	0.06	0.00	0.00	0.02	0.00	0.15	0.04	0.00	0.02
Marine ecotoxicity	0.00	0.01	0.00	0.00	0.00	0.00	0.48	0.00	0.00	0.00
Marine eutrophication	0.00	0.01	0.00	0.00	0.00	0.00	0.53	0.01	0.00	0.00
Mineral resource scarcity	0.00	0.00	0.00	0.00	0.00	0.00	0.59	0.00	0.00	0.00
Ozone formation, Human health	0.00	0.02	0.00	0.01	0.01	0.00	0.43	0.01	0.00	0.01
Ozone formation, Terrestrial ecosystems	0.00	0.02	0.00	0.01	0.01	0.00	0.44	0.01	0.00	0.01
Stratospheric ozone depletion	0.00	0.08	0.00	0.02	0.01	0.00	0.25	0.01	0.00	0.01
Terrestrial acidification	0.00	0.02	0.00	0.01	0.01	0.00	0.45	0.01	0.00	0.00
Terrestrial ecotoxicity	0.00	0.13	0.00	0.00	0.00	0.00	0.14	0.01	0.00	0.00
Water consumption	0.00	0.01	0.00	0.00	0.04	0.00	0.38	0.09	0.00	0.04
Average NSC over impact categories	0.00	0.04	0.00	0.01	0.01	0.00	0.47	0.02	0.00	0.01

A.3.2 Scenario Analysis

Table 23: Contribution of all input parameters for each impact category. Highlighted in red are the value above the threshold (in red for positive values, in green for negative one)

Process	Steel core Piles							Soil Stabilization			
Input parameter	Steel	Concrete	Transport of steel	Transport of machines	Transport of concrete	Transport of waste	Machine operation	Transport of cement	Transport of machines	Machine Operation	Cement
Impact category											
Global warming	40.93	0.77	2.99	0.02	0.03	0.01	0.75	0.06	0.02	1.89	19.80
Stratospheric ozone depletion	25.15	0.59	7.63	0.06	0.09	0.03	1.58	0.15	0.05	5.24	14.59
Ionizing radiation	-17.27	0.24	4.82	0.04	0.06	0.02	0.62	0.11	0.03	3.58	36.06
Ozone formation, Human health	42.64	0.60	2.02	0.02	0.03	0.01	1.30	0.05	0.01	3.31	15.26
Fine particulate matter formation	49.38	0.34	1.98	0.02	0.03	0.01	0.52	0.04	0.01	1.68	10.81
Ozone formation, Terrestrial ecosystems	43.72	0.57	2.00	0.02	0.03	0.01	1.24	0.05	0.01	3.16	14.68
Terrestrial acidification	44.67	0.52	2.34	0.02	0.03	0.01	0.78	0.05	0.01	2.58	15.40
Freshwater eutrophication	54.53	0.28	0.79	0.01	0.01	0.00	0.08	0.01	0.00	0.28	10.16
Marine eutrophication	53.28	0.47	0.74	0.01	0.01	0.00	0.09	0.01	0.00	0.30	2.11
Terrestrial ecotoxicity	14.48	0.40	12.96	0.14	0.20	0.08	0.21	0.35	0.11	0.70	7.43
Freshwater ecotoxicity	48.09	0.14	0.93	0.01	0.01	0.00	0.10	0.02	0.00	0.33	3.93
Marine ecotoxicity	47.87	0.15	1.24	0.01	0.01	0.01	0.11	0.02	0.01	0.35	4.00
Human carcinogenic toxicity	-78.57	0.06	0.24	0.00	0.00	0.00	0.00	0.00	0.00	0.03	1.84
Human non-carcinogenic toxicity	45.49	0.27	2.42	0.02	0.03	0.01	0.13	0.04	0.01	0.46	7.70
Land use	14.92	1.81	5.53	0.07	0.10	0.04	0.00	0.18	0.05	0.26	38.83
Mineral resource scarcity	59.27	0.06	0.25	0.00	0.00	0.00	0.08	0.00	0.00	0.19	5.99
Fossil resource scarcity	40.87	0.37	4.52	0.04	0.05	0.02	1.04	0.09	0.03	5.08	9.98
Water consumption	38.05	3.66	1.38	0.01	0.01	0.01	0.11	0.03	0.01	0.43	7.87
Average	42.18	0.63	3.04	0.03	0.04	0.02	0.49	0.07	0.02	1.66	12.58

Process	Ground Floor Slab			Anchoring of Sheet Pile Wall					
Input parameter	Transport of concrete	Lean concrete	Concrete	Steel	Transport of steel	Machine operation	Transport of machines	Transport of cement	Cement
Impact category									
Global warming	0.05	0.70	1.80	2.20	0.16	1.75	0.02	0.00	0.16
Stratospheric ozone depletion	0.13	0.58	1.38	1.35	0.41	3.68	0.05	0.00	0.10
Ionizing radiation	0.09	0.26	0.55	-0.93	0.26	1.44	0.03	0.00	0.28
Ozone formation, Human health	0.04	0.57	1.39	2.29	0.11	3.04	0.01	0.00	0.11
Fine particulate matter formation	0.04	0.32	0.79	2.66	0.11	1.22	0.01	0.00	0.07
Ozone formation, Terrestrial ecosystems	0.04	0.54	1.32	2.35	0.11	2.89	0.01	0.00	0.10
Terrestrial acidification	0.04	0.49	1.21	2.40	0.13	1.81	0.01	0.00	0.10
Freshwater eutrophication	0.01	0.26	0.66	2.93	0.04	0.19	0.00	0.00	0.05
Marine eutrophication	0.01	0.42	1.08	2.87	0.04	0.21	0.00	0.00	-0.02
Terrestrial ecotoxicity	0.30	0.43	0.92	0.78	0.70	0.50	0.11	0.00	0.03
Freshwater ecotoxicity	0.01	0.15	0.33	2.59	0.05	0.24	0.00	0.00	0.02
Marine ecotoxicity	0.02	0.16	0.35	2.57	0.07	0.26	0.01	0.00	0.02
Human carcinogenic toxicity	0.00	0.06	0.13	-4.23	0.01	0.01	0.00	0.00	0.01
Human non-carcinogenic toxicity	0.04	0.28	0.64	2.45	0.13	0.30	0.01	0.00	0.03
Land use	0.15	1.70	4.22	0.80	0.30	0.01	0.05	0.00	0.26
Mineral resource scarcity	0.00	0.06	0.13	3.19	0.01	0.18	0.00	0.00	0.03
Fossil resource scarcity	0.08	0.36	0.86	2.20	0.24	2.42	0.03	0.00	0.06
Water consumption	0.02	4.09	8.51	2.05	0.07	0.25	0.01	0.00	0.00
Average	0.06	0.63	1.46	2.27	0.16	1.13	0.02	0.00	0.08

Process	Sheet Pile Wall				Excavation of Masses			
Input parameter	Steel	Transport of steel	Transport of machines	Machine operation	Transport by ship	Transport by truck	Excavation (machines)	Transport of machines
Impact category								
Global warming	16.03	0.84	0.02	1.75	0.13	6.65	0.44	0.02
Stratospheric ozone depletion	12.80	2.15	0.05	3.68	0.05	17.51	0.90	0.05
Ionizing radiation	-17.75	1.36	0.03	1.44	0.02	12.43	0.24	0.03
Ozone formation, Human health	15.65	0.57	0.01	3.04	0.14	5.60	2.16	0.01
Fine particulate matter formation	21.97	0.56	0.01	1.22	0.04	5.28	0.88	0.01
Ozone formation, Terrestrial ecosystems	15.95	0.56	0.01	2.89	0.14	5.54	2.04	0.01
Terrestrial acidification	18.03	0.66	0.01	1.81	0.08	5.72	1.05	0.01
Freshwater eutrophication	27.58	0.22	0.00	0.19	0.00	1.63	0.07	0.00
Marine eutrophication	36.29	0.21	0.00	0.21	0.00	1.52	0.09	0.00
Terrestrial ecotoxicity	13.47	3.64	0.11	0.50	0.00	41.22	0.13	0.11
Freshwater ecotoxicity	40.56	0.26	0.00	0.24	0.00	1.86	0.10	0.00
Marine ecotoxicity	39.20	0.35	0.01	0.26	0.00	2.85	0.10	0.01
Human carcinogenic toxicity	14.35	0.07	0.00	0.01	0.00	0.36	-0.01	0.00
Human non-carcinogenic toxicity	33.21	0.68	0.01	0.30	0.01	5.21	0.10	0.01
Land use	7.91	1.55	0.05	0.01	0.00	21.09	-0.02	0.05
Mineral resource scarcity	29.68	0.07	0.00	0.18	0.00	0.53	0.08	0.00
Fossil resource scarcity	16.30	1.27	0.03	2.42	0.17	10.85	0.61	0.03
Water consumption	29.74	0.39	0.01	0.25	0.00	2.99	0.07	0.01
Average	22.58	0.86	0.02	1.13	0.04	8.27	0.50	0.02

Appendix 5

TECHNICAL NOTE: TOOLS FOR ASSESSMENT OF SUSTAINABLE ENVIRONMENTAL CONSEQUENCES OF GEOTECHNICAL WORKS

Til:	The Research Council of Norway
v/	Anne Kibsgaard
Kopi til:	
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Prosjekt:	SP Under Oslo
Prosjektleder:	Jenny Langford
Utarbeidet av:	Ingvild Størdal
Kontrollert av:	Stefan Ritter, Thea Lind Christiansen

Tools for assessment of sustainable environmental consequences of geotechnical works

Innhold

Kontroll- og referanseside

1 Introduction

Sustainable environmental consequences are often reported as climate gas emissions, or global warming potential (GWP). There are numerous tools available for calculation of GWP from projects and two relevant tools for NGI are VegLCA and SimaPro. VegLCA was developed by Statens Vegvesen for road construction projects and is widely used in connection with road construction. SimaPro is a more advanced tool and allows for analysis of complex projects and processes.

The aim of the following note is to compare GWP calculated using VegLCA and SimaPro.

2 Methods

Case study
The inventory data is based on the quantities of materials used for establishing the excavation pit for the Life Science Building in Oslo. The Life Science Building is planned as an extension of the existing campus of the University of Oslo, and the construction site is situated in the North of the campus (google maps coordinates 59.9453, 10.7203). The planned use of the building is teaching and research, and both hospital and educational services will be provided. The plan is to have a gross floor area of around 17 000 m^2, with a gross building area of around 97 000 m^2.

Goal and scope
The goal of this study was to evaluate the environmental impact from establishing a large excavation pit in typical Norwegian conditions with two different LCA tools and assess the difference in GWP calculated using the two tools.

Functional unit and system boundary
Functional unit for the analysis is impact per m^2 gross floor area. The system boundaries are as defined in Song et al. (2020) and the following major processes are included: Excavation, Stabilization, Sheet pile wall, Pipe pile wall, Anchors, Walers, Piles and Transport of excavated masses.

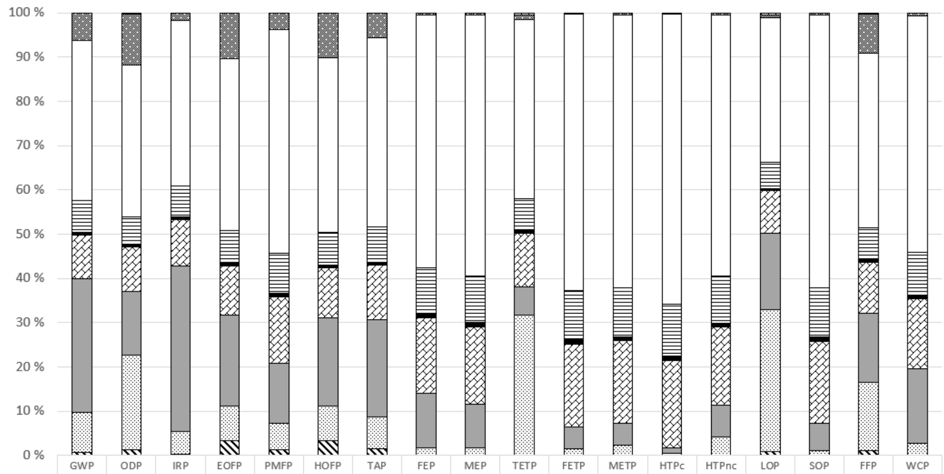
LCI
For the case study material quantities, machine hours and transport distances were included. The material quantities were provided by the contractor or subcontractor working at the site or collected from the as-built drawings after the excavation pit was finalized for a few of the categories. For some quantities it was necessary to make estimates based on calculations from as-built drawings. See detailed discussion on assumptions on material quantities, machine hours and transport distances in paper describing the SimaPro results. Machine hours estimate were made based on information from the contractor and subcontractor working at the site and previous experience from other excavation pits. The transport distances for machinery were calculated based on

distances from the contractor's and sub-contractor's storage. For materials the most realistic transport scenario was selected based on previous experience.

LCA tools
The LCA using SimaPro followed the methodology and requirements described in ISO 1404 and ISO 14044. The first LCA was calculated using the software SimaPro Analyst v. 9.1.1.7, and the impact assessment method ReCiPe 2016 V1.1 midpoint method, Hierarchist version. (Huijbregts et al., 2017). To compare, a second LCA was calculated using VegLCA v5.06B.

3 Results

The results from the LCA performed using SimaPro is shown in Figure 1, while the results from the climate gas impact calculated using VegLCA is shown in Figure 2.



	GWP	ODP	IRP	EOFP	PMFP	HOFP	TAP	FEP	MEP	TETP	FETP	METP	HTPc	HTPnc	LOP	SOP	FFP	WCP
⊞ Sum transport materials and machines	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
▩ Sum machine hours	6	12	2	10	4	10	6	1	1	1	0	0	0	1	1	0	9	1
☐ Piles	36	34	37	39	50	39	43	57	59	40	62	62	66	59	33	62	39	53
▤ Anchor and walers	7	6	7	7	9	7	8	10	11	7	11	11	12	11	6	11	7	10
■ PPW	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
☒ SPW	10	10	11	11	15	11	12	17	18	12	19	19	20	18	10	18	12	16
▣ LCC	30	14	37	21	14	20	22	12	10	6	5	5	1	7	17	6	16	17
⚃ Transport of excavated masses	9	21	5	8	6	8	7	2	2	31	2	2	0	4	32	1	15	3
◪ Excavation	1	1	0	3	1	3	1	0	0	0	0	0	0	0	1	0	1	0

Figure 1. Relative contribution to impact categories from the major categories included for the excavation pit at the Life Science Building.

The total GWP calculated is 33 000 000 kg CO2-eq. using VegLCA, while the total GWP calculated using SimaPro is 32 000 000 kg CO2-eq.

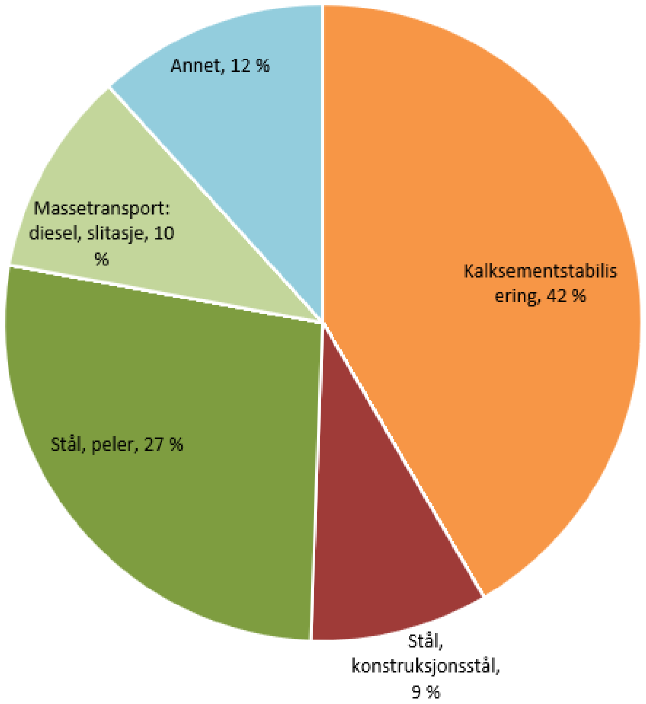


Figure 2. Relative contribution to climate gas emissions from the major categories included for the excavation pit at the Life Science Building

4 Discussion

Both LCA tools show that the piles and the soil stabilization prior to excavation contribute significantly to the GWP. However, the SimaPro calculations show that the piles are the largest contributor, while VegLCA show that the soil stabilization is the largest contributor. At the Life Science Building excavation pit Multicem was used for soil stabilization. Multicem consists of 50% cement, 50% CKD (cement kiln dust). CKD is a by-product from the production of cement and replacing half of the cement with CKD lowers the CO2-emissions from the production. It is not possible to select a binder type with a by-product for soil stabilization in the early phase tool of VegLCA. The results show, as expected, that if accurate representation of the emissions is necessary, SimaPro should be used. While if an approximate, first stage calculation is sufficient, the early phase tool of VegLCA could be used. The late phase/detailed tool of VegLCA allows for entry of product specific impact factors.

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