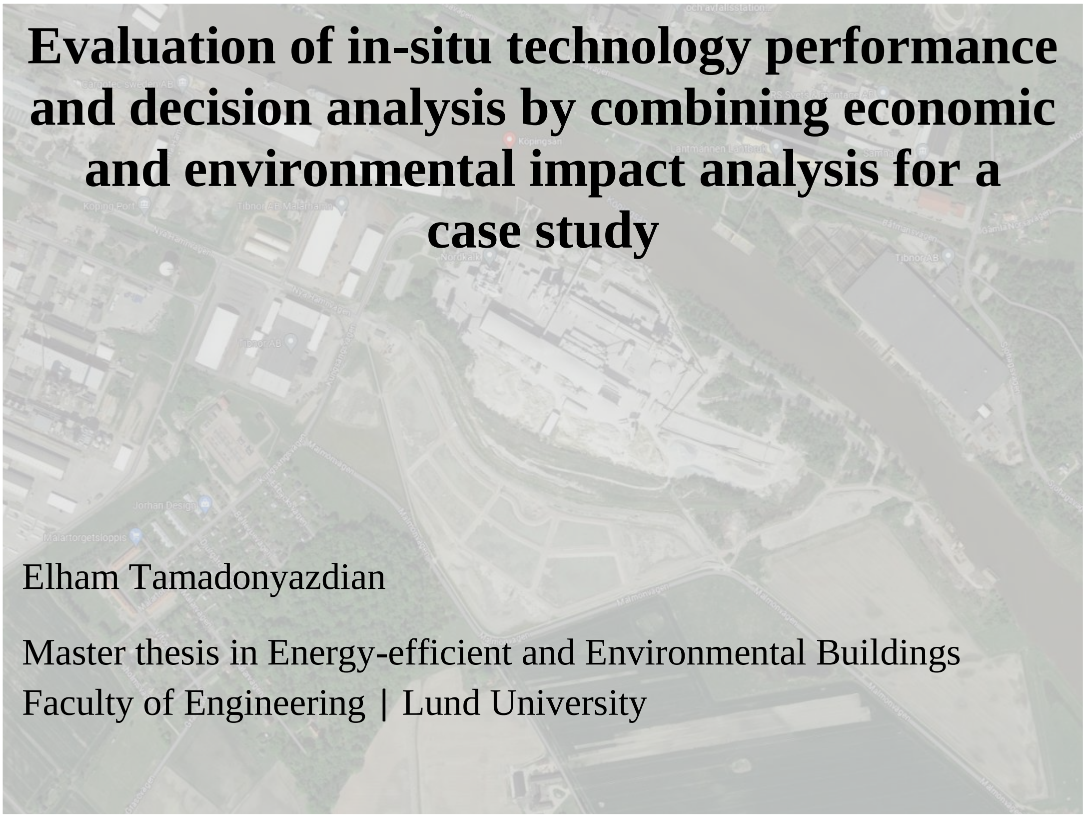

Evaluation of in-situ technology performance and decision analysis by combining economic and environmental impact analysis for a case study

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Master thesis in Energy-efficient and Environmental Buildings
Faculty of Engineering | Lund University

Lund University

Lund University, with eight faculties and a number of research centers and specialized institutes, is the largest establishment for research and higher education in Scandinavia. The main part of the University is situated in the small city of Lund which has about 112 000 inhabitants. A number of departments for research and education are, however, located in Malmö. Lund University was founded in 1666 and has today a total staff of 6 000 employees and 47 000 students attending 280 degree programs and 2 300 subject courses offered by 63 departments.

Master Program in Energy-efficient and Environmental Building Design

This international program provides knowledge, skills, and competencies within the area of energy-efficient and environmental building design in cold climates. The goal is to train highly skilled professionals, who will significantly contribute to and influence the design, building or renovation of energy-efficient buildings, taking into consideration the architecture and environment, the inhabitants' behavior and needs, their health and comfort as well as the overall economy. The degree project is the final part of the master's program leading to a Master of Science (120 credits) in Energy-efficient and Environmental Buildings.

Peab

Peab is a renowned construction and civil engineering company operating in Sweden and several other Nordic countries. With a rich history spanning over six decades, Peab has established itself as a leader in the construction industry, known for its expertise, innovation, and commitment to sustainability. The company has undertaken numerous projects across various sectors, including infrastructure, residential, commercial, and industrial construction. Peab's focus on quality, safety, and environmental responsibility has earned it a strong reputation in the industry [1].

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Keywords:

Stabilization, Dredging, Solidification, Cement mixtures, Binders, In-situ technology, Environmental impact categories, Life cycle assessment (LCA), Economic analysis, Life cycle costing (LCC), Global Warming Potential (GWP), Acidification Potential (AP), Eutrophication Potential (EP), Ozone Layer Depletion Potential (ODP), Single-Point Rate (SPR).

Abstract

In the contemporary global context, the global focus on reducing environmental impacts in any formats has intensified. This study intends to assess the environmental impacts and life cycle costs associated with the A1-A5 stages (production and construction stages) of the Köping Port project and eight additional proposed scenarios. The Solidification/ Stabilization method along with the in-situ technology was utilized in this project. The study is based on a port with an area of 48,586 m^2 located in Köping, Sweden which was stabilized with treated soil, a composition of sediment, cement, slag, and activated carbon.

This study was performed in different sequenced steps of data collection, LCA modeling, environmental assessment, economic analysis, and future decision analysis. Data collection for the project was conducted by collecting project-specific data regarding the project process, consumed materials and involved workforce as well as related costs. Data collection process also continued by investigating and selecting the most appropriate EPDs for slag and activated carbon materials. Based on the type of cement and different binder mixture, 8 scenarios were defined. To investigate the environmental impacts, the Life Cycle Assessment (LCA) was performed by GaBi (LCA for Experts) and Excel files. The next step was assessing the economic aspect by the Life Cycle Costing (LCC) method. Then, by applying the Single-Point Rate (SPR) calculation, decision analysis was conducted and the best scenario was selected regarding the integration of LCA and LCC.

LCA results from four investigated environmental categories (GWP, AP, EP, ODP) in this study, show that there is a similar trend between four different categories. The pattern is that always scenario with a higher amount of cement in the binder mixture (40%) within each distinct cement type has the highest environmental impact which is followed by a scenario with 30% cement in the binder mixture and finally scenario with 20% used cement in the mixture composition. The LCC results underscore the pivotal role of cement in shaping the overall expenditure of the project within the analyzed stages.

According to the results, Scenario 2 which includes cement type I, with the binder mixture of 20%-80% for cement and slag respectively, was selected as the optimum scenario. This result was obtained based on all three options that were defined for weighting factors for the LCA and LCC. In fact, this scenario demonstrated almost 29% lower environmental impact and around 1.5 MSEK less initial cost compared to the base case which cement type 1, with the binder mixture portion of 20% cement and 80% slag is utilized in it.

To my son:
ATRIN

Acknowledgments

I would like to extend my appreciation to my main supervisor, Karin Farsäter, for her support and invaluable guidance throughout the entirety of this project. Her expertise and guidance were instrumental in successfully conducting the environmental impact assessment. Despite her busy schedule, she graciously provided outstanding assistance, for which I am sincerely thankful.

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Nomenclature

Abbreviation	**Description**
AP	Acidification Potential
CO2	Carbon dioxide
CFC11	Trichlorofluoromethane
EP	Eutrophication Potential
EPD	Environmental Product Declaration
GWP	Global Warming Potential
GaBi	LCA for Experts software
$Kg_{Co2\ eq.}$	Carbon dioxide equivalent in kilogram
kg	Kilogram
Km	Kilometre
LCA	Life Cycle Assessment
LCI	Life Cycle Inventory
LCIA	Life Cycle Impact Assessment
LCC	Life Cycle Cost
LCCA	Life Cycle Cost Analysis
m^2	Square meter
m^3	Cubic meter
NPV	Net present Value
ODP	Ozone Depletion Potential
PAHs	Polycyclic Aromatic Hydrocarbons
PO_4^{3-}	Phosphate
SEK	Swedish krona
SO2	Sulphur Dioxide
SPR	Single-point Rate
SDGs	United Nation’s Sustainable Development Goals

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1 Introduction

In today's world, the global focus on reducing environmental impacts in any formats has intensified. This challenge has emerged as significant cross-cutting issues that demand attention from nations worldwide. Reference to the United Nations' Sustainable Development Goals (SDGs) and the commitments outlined in the Paris Agreement highlights the pivotal role of the construction and real estate sectors in the ongoing discussions on sustainable development. These sectors play a crucial part in shaping sustainable practices and driving progress towards achieving the SDGs and meeting the global climate targets set in the Paris Agreement [2].

Life Cycle Assessment (LCA) has emerged as a widely accepted methodology for evaluating the environmental impact of construction projects throughout their entire lifespan. LCA assesses the environmental burdens of raw material extraction, construction processes, use and maintenance, and end-of-life scenarios. By considering the complete lifespan, LCA enables a holistic understanding of the environmental implications of a project [3]. LCA calculation tools are software applications designed to assess the environmental impact of products and processes across their entire lifecycle. These tools quantify resource consumption, emissions, and other environmental factors. They vary in complexity, from user-friendly options with preloaded databases and simplified interfaces, such as SimaPro and OpenLCA, to more advanced platforms like GaBi and Brightway that offer customization and in-depth analysis capabilities [4]. Within the tools, GaBi (LCA for Experts) software has gained recognition as a leading and scientifically rigorous tool, enabling comprehensive analysis of environmental impacts across multiple life cycle stages. GaBi provides a robust framework for assessing the environmental performance of construction materials, processes, and systems [5].

In addition to environmental impact, Life Cycle Cost (LCC) calculations have become an essential aspect of project evaluation. LCC calculations take into account not only construction costs but also operational and maintenance expenses over the project's lifespan. By considering the long-term financial implications, life cycle cost analysis enables decision-makers to identify cost-effective solutions while balancing economic feasibility and sustainability [3]. This approach supports the identification of strategies that minimize costs and maximize the value delivered throughout the life cycle of a project [6].

Stabilization and solidification techniques are methods used to manage and treat hazardous waste materials by transforming them into a stable and less harmful form. These techniques typically involve mixing waste with binders or additives to create a solid material that encapsulates the contaminants and prevents their migration. Common binders include cement, lime, and polymers. The resulting solidified waste can be safer for disposal or even repurposed in construction applications [7].

Dredging operations are routinely conducted worldwide in channels, ports, and rivers to maintain navigational depth. As a result, a substantial volume of sediment, amounting to hundreds of millions of cubic meters annually, needs to be transferred. These sediments possess high water content, low compressive strength, high compressibility, and toxic compounds, leading to direct environmental impacts. Consequently, the safe disposal of dredging sediments has become a significant global environmental concern. Stabilization/Solidification (S/S) has emerged as a widely recognized and practical approach for managing contaminated dredged sediments. The term "solidification" refers to the physical enhancement of a mixture, while "stabilization" signifies the chemical transformation of contaminants into less soluble, mobile, or toxic forms [8]. In the S/S method, binders are mixed with the sediments to improve their geotechnical properties and encapsulate the polluted components within the paste matrix, thereby enabling their recycling as construction materials [9]. The S/S method harnesses both in-situ and ex-situ technologies to effectively immobilize contaminants in hazardous waste.

In-situ technology refers to a remediation approach that aims to address environmental contamination directly at the site, without the need for excavation or removal of contaminated materials. It involves the application of various techniques and processes to treat soil, groundwater, or other media in their original location. In-situ technologies offer several advantages, including reduced disruption to the surrounding area, minimized transport and handling of hazardous materials, and potentially lower costs compared to traditional ex-situ methods. Ex-situ technology refers to a technology which involves removing and treating hazardous materials away from their original location, often in a controlled facility or treatment plant. Common in-situ remediation techniques include chemical oxidation, bioremediation, phytoremediation, and in-situ thermal treatment. These approaches utilize chemical agents, microorganisms, plants, or heat to degrade, transform, or immobilize contaminants in the subsurface. In-situ technology plays a crucial role in the sustainable management of contaminated sites and has gained significant attention due to its potential for effective and environmentally friendly remediation [10].

Numerous projects have adopted these technologies and methodologies to mitigate their environmental footprint and facilitate the reuse of dredged sediment materials. One instance is the Port Newark project in New Jersey. This endeavor addressed contamination issues spanning approximately 3.2 hectares of soil at the site, which were tainted with arsenic, chromium, and polycyclic aromatic hydrocarbons (PAHs). The remediation strategy employed in-situ soil mixing to treat 17,000 cubic meters of soil within the depth range of 0.6 meters to 3.7 meters. This treatment process encompassed the preliminary excavation of contaminated materials, the systematic reintroduction of stockpiled materials into the excavated area using lifts, and the application of solidification/stabilization treatment to each lift via an in-situ blender head. As another case in point, consider the Re-Use of New York Harbor Sediments project. In this endeavor, millions of cubic meters of sediment underwent a solidification/stabilization process based on cement. This transformative treatment effectively immobilized heavy metals, dioxins, PCBs, and other organic contaminants present in the sediment. Consequently, the treatment not only remediated the sediment but also turned it from an environmental liability into a valuable resource as structural fill material. The process involved transporting dredged sediment via barge to a pier. At the pier, cement was blended with the sediment while it remained within the barge, using an excavator-mounted mixing head. Subsequently, the treated material was extracted from the barge and repurposed as structural fill [11].

1.1 Objectives

The objective of this thesis is to assess the environmental impacts and life cycle costs associated with the A1-A5 stages (production and construction stages) of the Köping Port project and eight additional proposed scenarios. The evaluation will focus on the performance of in-situ technology, considering both environmental and economic aspects. This study will specifically investigate the following environmental impact categories:

1- Global Warming Potential (GWP)
2- Acidification Potential (AP)
3- Eutrophication Potential (EP)
4- Ozone Layer Depletion Potential (ODP)

The goal of this study is to provide valuable insights and recommendations for making informed decisions, considering both the environmental impacts and financial implications of the project and its alternatives.

1.2 Research Questions

This thesis aims to address the following questions:

- What is the environmental impact of the Köping project?
- What are the results for the financial viability of the project?
- Which processes and resources in the project have the greatest impact on the two dimensions of sustainability (environmental and financial)?
- What are the environmental impacts of each scenario in terms of GWP, AP, EP, and ODP categories?
- Which scenario is the best in terms of integration of LCA and LCC?
- What is the performance of the optimum scenario in terms of financial and environmental impacts?

1.3 Workflow

The workflow in the present study is as demonstrated in Figure 1 which follows the below steps:

Literature Review: The initial step of this master thesis involved conducting a comprehensive literature review. This review focused on environmental impact assessment, LCA, LCC, solidification/ stabilization, in-situ technology, and decision analysis within the context of this project, with a specific emphasis on stabilized ports and associated environmental considerations. By reviewing relevant scholarly articles, reports, and industry publications, a solid understanding of the latest progress in this field is achieved.

Data Collection and Scenario Definition: The second phase of this research entailed gathering project-specific data from Peab, the responsible company1 for the stabilized port project in Köping, Sweden. This included acquiring information regarding the materials, construction, processes, machinery, and relevant project documentation. Additionally, comprehensive data on material costs was gathered by contacting pertinent companies and procuring pricing information. Moreover, among all included materials and processes, Environmental Product Declarations (EPDs) were complied for the slag and activated carbon materials to be utilized in the LCA. After required data collection, various scenarios were defined based on variations in material selection and different mixture portion of materials.

Life Cycle Assessment (LCA): The subsequent step involved conducting an LCA using the GaBi (LCA for Experts) software. By inputting the collected data and considering the defined scenarios, LCA calculations were performed within GaBi. The LCA analysis encompassed various environmental impact categories, such as GWP, AP, and others of interest. To supplement the LCA calculations, Excel sheets were utilized for additional analyses or customized calculations, if deemed necessary based on research objectives.

Life Cycle Cost (LCC) and Decision Analysis: After completing the LCA, the evaluation of LCC was done associated with the present situation and different scenarios. This involved utilizing Excel sheets to calculate the costs of materials, workmanship, machinery and consumed fuel. Subsequently, LCA and LCC results were integrated to assess the environmental and economic performance of each scenario. By employing Single Point Rate method (SPR) [12], the trade-offs between environmental impact and life cycle cost were evaluated. SPR was used to compare the different scenarios and identify the most optimum option.

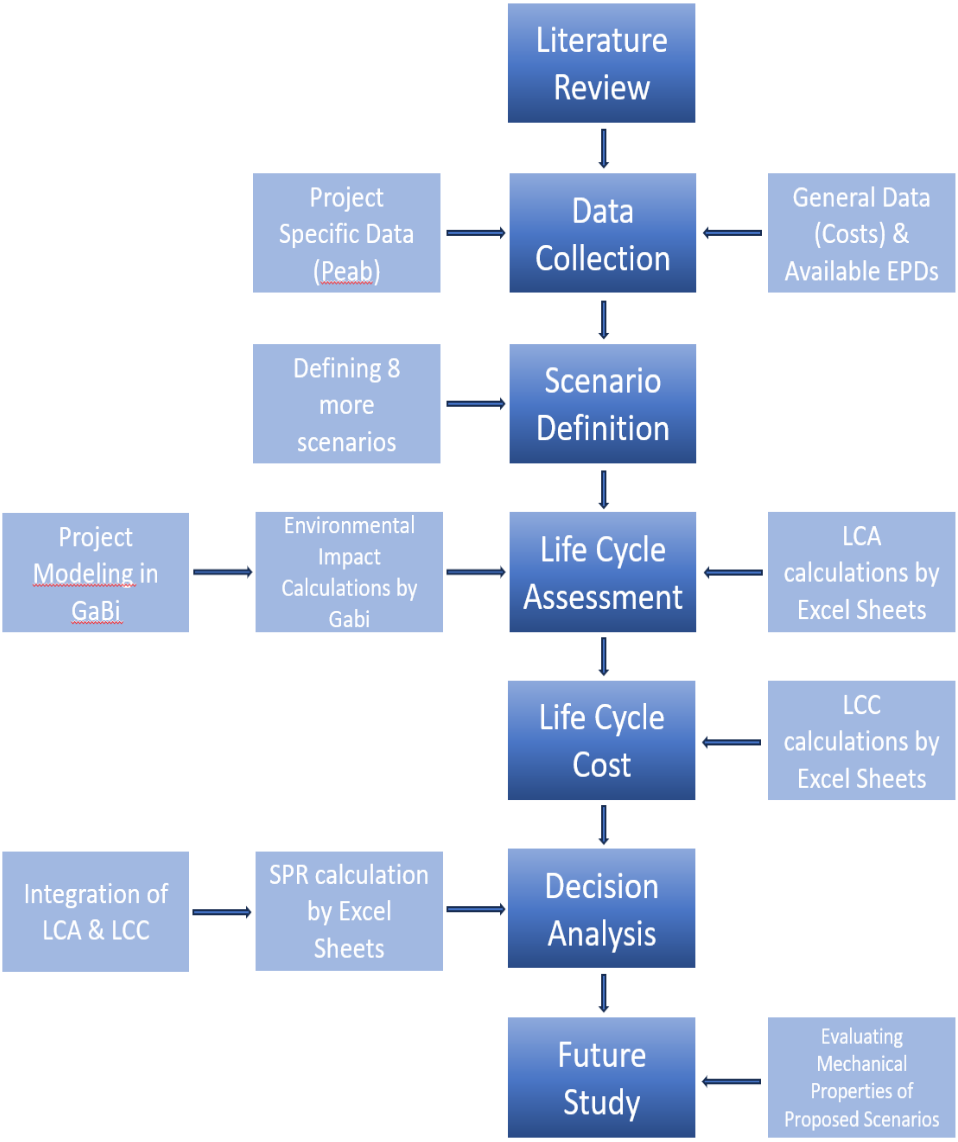

Figure 1: Master thesis project workflow

2 Methodology

The first step addressed within the Methodology section is the LCA. This involves defining the declared unit of the assessment, determining the system boundaries, and identifying the relevant environmental impact categories. Data collection and document analysis, were employed to gather necessary information. The Life Cycle Inventory (LCI) stage involved collecting data on raw material inputs, energy consumption, and emissions across different phases of the stabilized port project. The subsequent life cycle impact assessment evaluated the potential environmental impacts associated with the project, with focusing on areas such as greenhouse gas emissions.

The second step addressed is the LCC. This involved identifying and categorizing various cost components of the stabilized port project. Capital expenses, operational expenses, and other financial considerations were considered. Methods such as historical data, industry benchmarks, and expert opinions were utilized to estimate and analyze the life cycle costs of the project. The LCC phase aimed to provide insights into the financial implications of the project, identify cost drivers, and facilitate decision-making regarding project feasibility and sustainability.

The final step discussed in the Methodology section is Decision Analysis. This involved the establishment of evaluation criteria to assess both environmental impact and life cycle cost. The chosen criteria were selected to align with the research objectives and to ensure the project evaluation. To facilitate decision-making, SPR method was applied. This method integrates the evaluation criteria and provides a framework for ranking and prioritizing alternative scenarios or options based on their performance concerning the established criteria.

2.1 Case Study

The Köping Port Deepening and Harbor Basin Expansion Project is an integral part of the Mälarprojektet, aimed at enhancing navigational efficiency from Södertälje lock to Köping and Västerås harbors. Köping municipality has obtained permission to deepen and widen the fairway and harbor basin within the Köping port area. Additionally, the project has been granted approval to stabilize and solidify dredged sediments for utilization as construction material. Spanning an area of 48,586 m^2, this project promises to create a future industrial zone, ensuring improved storage, expansion areas, and operational facilities for existing and upcoming industries. The scope of the project involves establishing an industrial area on existing farmland located directly south of Nordkalk's industrial facility and approximately 0.7 km southwest of Djuphamnen, Köping's port (Figure 2). A primary objective is to develop road access to Nya Hamnvägen in the western part of the area. The project plans to utilize dredged sediments from Köping's port area through stabilization and solidification, adopting sustainable practices to promote environmental preservation and efficient land development.

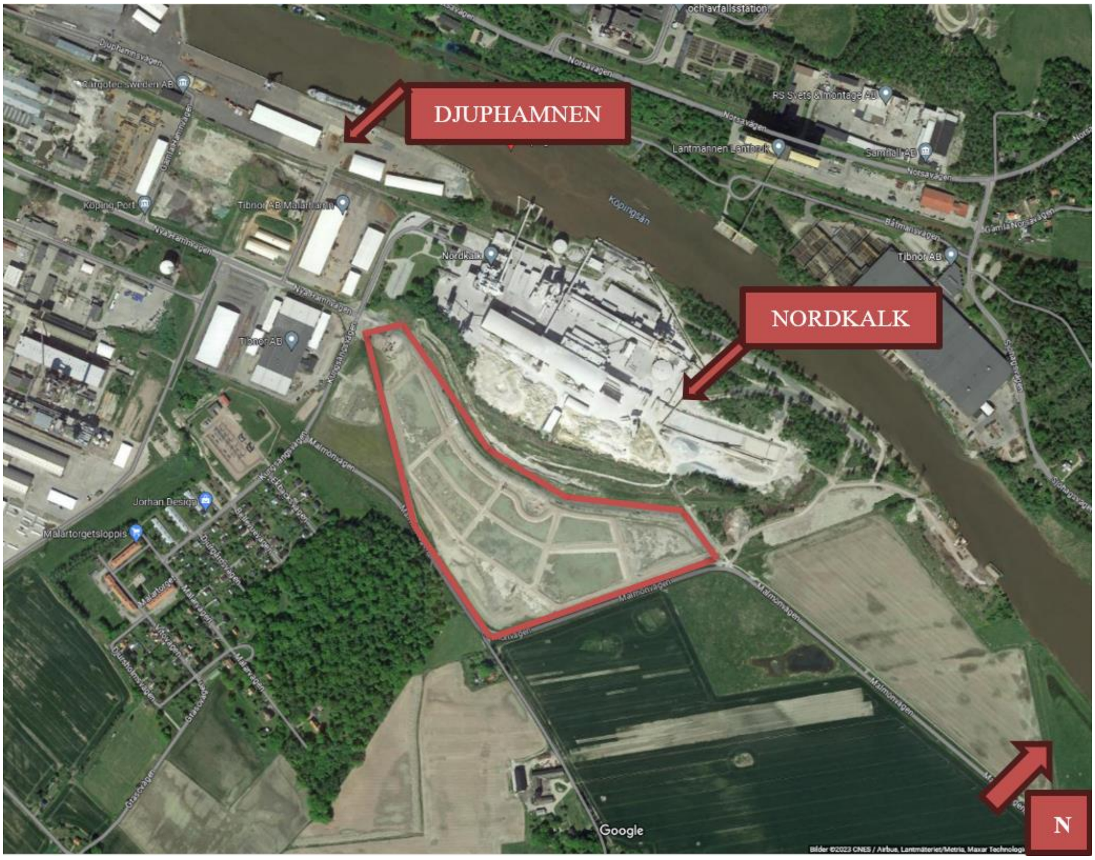

Figure 2: Overview of the project location

The contract work encompasses extensive preparatory tasks to facilitate the successful execution of the operational area plan. Key elements include constructing access roads, establishing a temporary quay along Köpingsån, and planning the transportation route from the temporary quay area to the operational zone. The removal of existing quays and clearing of the work zone are undertaken, along with tree felling and earthworks for creating areas to utilize dredged sediments. Notably, comprehensive drainage systems, pipelines for stormwater, and noise barriers will be implemented to ensure smooth operations. The construction of the operational area entails a foundation of stabilized and solidified mud masses, complemented by sealed embankments made of crushed rock. This cohesive surface will be connected to the entrance road from Nya Hamnvägen, adapting the completed area's size based on the quantity of mud masses utilized. The project aims to efficiently transfer mud masses, manage excess water, and mitigate any environmental impact while adhering to strict conditions and permits. The Köping Port Deepening and Harbor Basin Expansion Project is strategically located within the existing agricultural land between Malmönvägen and Nordkalk's industry embankment. While the western part of the area lies approximately 0.5

km away from Djuphamnen, the eastern part is situated about 1.1 km from the port (Figure 3). The temporary quay is planned along the southern shore of Köpingsån, approximately 1.5 km east of Djuphamnen and 0.5 km southwest of the oil quay. Operating within the RH 2000 vertical reference system and Sweref 99 1630 horizontal coordinate system, the project is well-positioned to benefit from the proximity to major road connections like Malmönvägen, Nya Hamnvägen, and county road 250. Adjacent to Nordkalk's industrial area and the Mälarhamnar port, the project ensures compatibility with neighboring operations. Tibnor, Yara, the Kungsängen residential area, and a substation and transformer station operated by Mälarenergi and Vattenfall are taken into consideration for seamless execution. Thorough analysis and documentation of existing lines guarantee that the project is in compliance with safety regulations and prevents any disruption to vital utilities. The Köping Port Deepening and Harbor Basin Expansion Project showcases an appropriate approach to improve navigational routes and industrial development. Utilizing stabilized dredged sediments, the project aims to transform farmland into a modern industrial area with efficient access and environmentally conscious practices. With a focus on adherence to conditions and permits, and consideration of adjacent operations, this transformative project is set to enhance Köping's port infrastructure while maintaining harmony with the local environment and neighboring facilities [13].

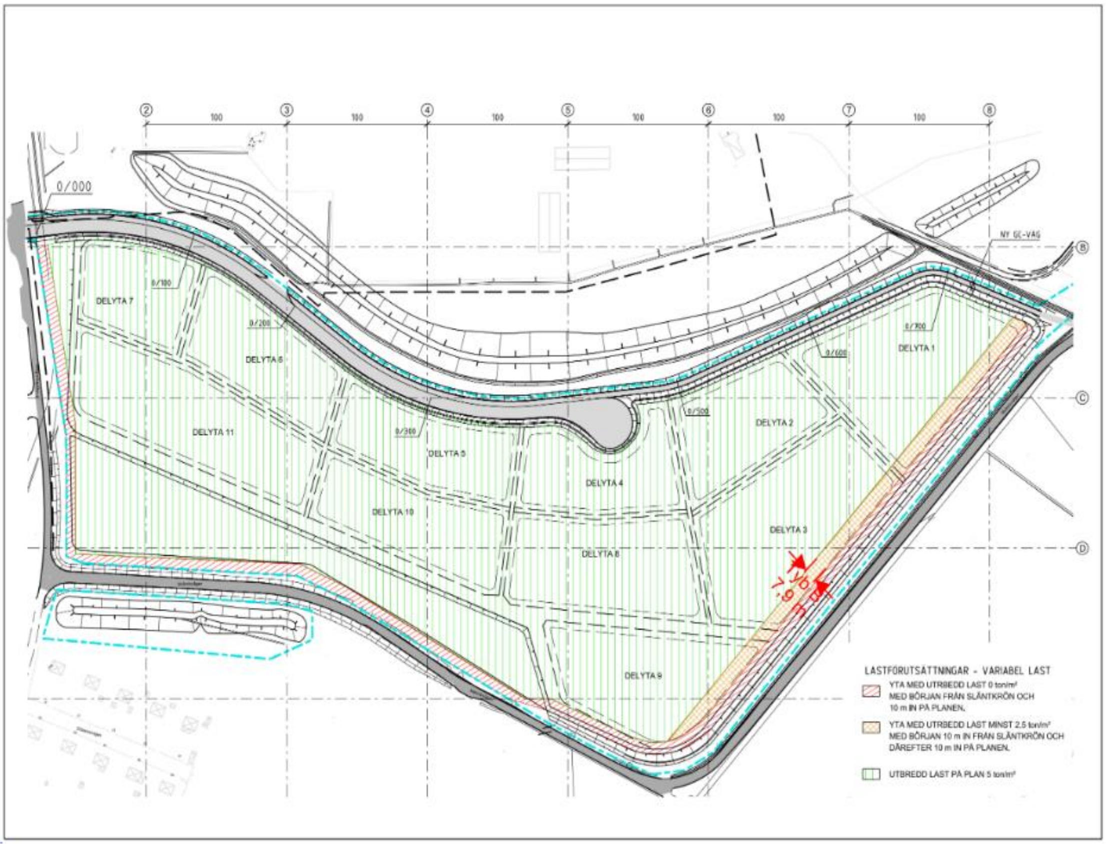

Figure 3: Site-plan specification

2.1.1 Present Situation

The present situation of the Köping stabilized port project involves utilizing specific materials for the stabilization process. This section presents an overview of the primary materials utilized in the study, specifically cement, slag, activated carbon, and dredged sediment from the sea. Furthermore, it outlines the composition of the mixture, highlighting varying proportions of these materials, which serves to provide insights into the stabilization process.

Cement: Cement, a widely used binding agent in construction, plays a crucial role in construction projects, and it is known for its ability to provide strength and durability to structures [14]. In this project, 4,600,872 kg of cement type I, which is 28.6% of the binder mixture composition, consists of cement. The use of cement enhances the cohesive properties of the mixture and contributes to the long-term stability of the port.

Slag: A byproduct of the iron and steel industry, offers numerous benefits when used as a component in the stabilization process. It possesses pozzolanic properties, which enhance the strength and durability of the mixture [15]. 10,734,302 kg of the binder mixture composition comprises slag with its corresponding portion of 66.6%. The inclusion of slag contributes to reducing the environmental impacts associated with the disposal of this industrial waste [16].

Activated Carbon: Activated carbon, with its high surface area and adsorptive properties, is utilized in the stabilization process to mitigate potential environmental contamination [17]. 774,310 kg or 4.8% of the binder mixture composition incorporates activated carbon. This material aids in the adsorption of pollutants and contaminants, thereby reducing their impact on the surrounding ecosystem and promoting environmental sustainability [18].

Dredged Sediment: Using dredged sediment from the sea presents an innovative approach to reducing the consumed material in the stabilization process. In this regard, sediment is excavated from the sea and transported to the site of the project. Then it will be mixed with the other binders to use in the stabilization process. In this project, in-situ technology is applied as the placement of the sea (sediment source) and intended port is the same. 96,584,700 kg of sediment is excavated from the sea for this project. The detail of the excavated sediment material composition is presented in Table 1.

Table 1: Sediment material composition

Material	Total weight/ Tonne
Sand	4 075.3
Silt	26 489.5
Clay	10 188.3
Sea water	55 831.7
Total sediment	96 584.7

Mixture Composition (stabilized soil): The stabilized port project employs a designed mixture composition to optimize the desired properties and performance. The specific portion of each material, as determined by the project requirements, is as follows: 4.08% cement, 9.53% slag, 0.69% activated carbon, and 85.71% dredged sediment.

2.1.2 Proposed Scenarios

In this study, a diverse set of alternative scenarios was proposed to investigate the environmental and economic impacts of possible options comprehensively. These scenarios were formulated to explore different possibilities and evaluate various options within the framework of LCA and LCC. By considering multiple scenarios, the aim was to provide an understanding of the project's sustainability implications and identify potential areas for improvement.

The proposed scenarios encompassed three variables, including different “types of cement” and “different portions” of cement and slag in the binder mixture. Each scenario represented a unique combination of parameters, allowing for a comparative analysis of their environmental impacts and associated costs. By evaluating these scenarios, it became possible to identify the most favorable options in terms of both environmental sustainability and cost-effectiveness.

To better illustrate the eight proposed scenarios and facilitate a clear comparison, Table 2 and 3 outline each scenario's key characteristics and attributes. Referencing these tables will allow readers to gain an overview of the alternative scenarios under consideration and navigate the subsequent discussions on the LCA and LCC findings for each scenario.

Table 2: Proposed scenarios

Scenario	Type of Cement	Ratio of Cement	Ratio of Slag
Present Situation	type I	30%	70%
Scenario 1	type I	40%	60%
Scenario 2	type I	20%	80%
Scenario 3	type II	30%	70%
Scenario 4	type II	40%	60%
Scenario 5	type II	20%	80%
Scenario 6	type III	30%	70%
Scenario 7	type III	40%	60%
Scenario 8	type III	20%	80%

Table 3: amount of each material in different portion of binder mixture in Kg

Used material	Slag 70% & Cement 30%	Slag 80% & Cement 20%	Slag 60% & Cement 40%
Cement	4 600 872	2 761 166	5 991 117
Slag	10 734 302	12 573 452	9 343 501
Activated Carbon	774 310	774 310	774 310

2.2 Life Cycle Assessment (LCA)

Life Cycle Assessment (LCA) is a scientifically grounded methodology used to evaluate the environmental impact of a product, process, or system throughout its entire lifespan, from raw material extraction to disposal. LCA involves the systematic collection, analysis, and interpretation of data on resource use, energy consumption, emissions, and potential environmental impacts. By considering a wide range of impact categories, such as climate change, resource depletion, and human toxicity, LCA provides valuable insights into the environmental performance of different alternatives and helps identify areas for improvement. This scientific approach enables us to promote sustainable development by considering the complex interactions and trade-offs inherent in the life cycle of a product or system [3].

2.2.1 Goal and Scope

The goal of the LCA for the Köping port project is to assess and evaluate the environmental impact throughout the “production” and “construction” phases of the project. The primary objective is to gain a comprehensive understanding of the project's sustainability performance and identify areas for improvement. The ultimate goal is to provide insights and recommendations that can contribute to developing a more sustainable and environmentally responsible port project.

In this study, the scope of the LCA encompasses the first two stages of the port, including the extraction of raw materials and transportation to the site, and construction activities. It considers all relevant processes and activities within the system boundaries.

2.2.2 System boundaries (Life Cycle Stages)

The system boundaries would start from the extraction of raw materials (A1) required for the construction of the port. This includes the sourcing and extraction of materials such as cement, slag, activated carbon, and any other materials used in the stabilization process. The boundaries would also include the transportation of these materials to the construction site (A2) in Köping. Within the system boundaries, the construction phase (A5) of the port would be considered, which involves the actual stabilization process. This phase would include energy consumption for activities associated with the construction processes. As in-situ technology is employed in this project, the mixing of all materials to make the final product (stabilized soil) for stabilizing the port (A3) is taking place at the production site. Transporting finished product to the construction site (A4) is almost done within the project area, so 50 m is considered for the distance between two points. In this case, stage (A5) occurs with the intended stabilized area. Figure 4 illustrates these stages for the present situation.

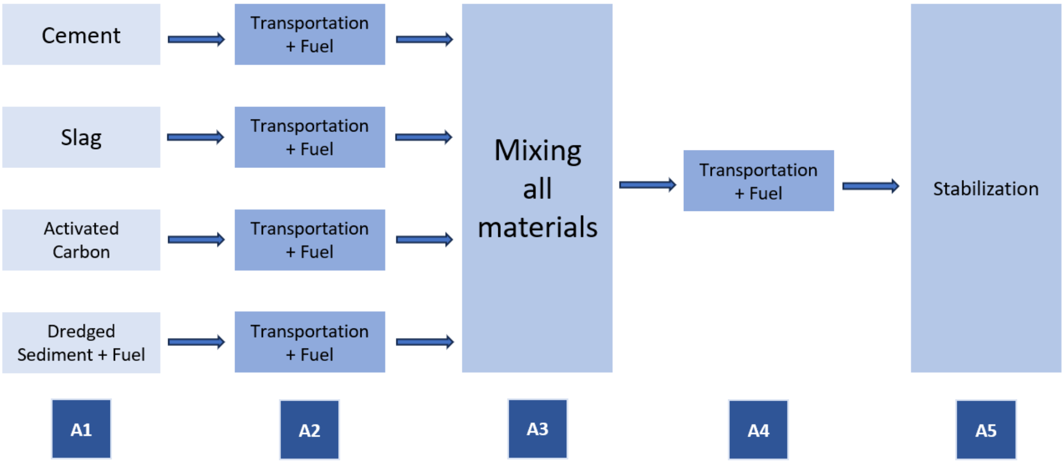

Figure 4: System boundaries for the Köping Stabilized Port (A1-A5)

2.2.3 Declared Unit

The “declared unit” is a standardized unit that allows for comparison and communication of the project's environmental impacts. The "declared unit" in the context of this project refers to the specific quantifiable measure to express the environmental performance of the Köping port project and is defined as the “finished and ready to use stabilized port with 48,586 m^2 surface area located in Köping, Sweden”.

2.2.4 Software

For conducting the LCA in this project, GaBi (LCA for Experts) software,version 10.6.1, was employed, utilizing two different databases which are “Ecoinvent” and “Sphera” databases. GaBi is a widely recognized tool specifically designed for LCA analysis, known for its comprehensive and reliable databases that provide extensive LCI data that facilitates the selection of the appropriate raw materials and processes according to the real situations [19]. Using GaBi (LCA for Experts), the project benefited from its robust functionality, allowing for integrating of various inputs and parameters along with an Excel file required for a thorough LCA. The two different databases employed provided access to a wide range of data related to materials, processes, and environmental impact categories.

2.2.5 LCA inputs

In order to accurately model the processes of the project within the designated software, GaBi (LCA for Experts), project-specific data was provided by Peab. This data, analyzed and evaluated, served as the foundation for selecting the most appropriate materials and processes to be incorporated into the GaBi (LCA for Experts). Integrating project-specific data, materials and processes, forms the base for the analysis of the environmental impacts associated with the Köping stabilized port. Used datasets for chosen materials and processes in this LCA modelling can be found in Table 4.

Table 4: Project inputs

Material/ Process	Used dataset in GaBi	Corresponding stage	Quantity	Unit
Cement	REF: Cement (CEM I 42.5) (burden free binders) (EN15804 A1-A3)	A1	4.6E006	kg
Slag	Available EPD	A1	1.07E007	kg
Activated Carbon	Available EPD	A1	7.74E005	kg
Dredged Sediment	Customized Process	A1	9.66E007	kg
Consumed fuel for sediment excavation	REF: Diesel mix at refinery	A1	1.13E004	kg
Transportation of Cement from the factory to the site	GLO: Truck-trailer, Euro 6 A-C, 34 - 40t gross weight / 27t payload capacity	A2	0.4	km
	REF: Diesel mix at refinery	A2	38.8	kg
Transportation of Slag from the factory to the site	GLO: Truck-trailer, Euro 5, 34 - 40t gross weight / 27t payload capacity (with SCR)	A2	144	km
	REF: Diesel mix at refinery	A2	3.3E004	kg
Transportation of Activated Carbon from the factory to the site	GLO: Truck-trailer, Euro 6 A-C, 34 - 40t gross weight / 27t payload capacity	A2	526	km
	REF: Diesel mix at refinery	A2	8.58E003	kg
Transportation of Excavated Sediment from sea to the site	GLO: Truck-trailer, Euro 5, 34 - 40t gross weight / 27t payload capacity (with SCR)	A2	0.8	km
	REF: Diesel mix at refinery	A2	1.66E003	kg
Mixing of all materials	Customized process	A3	Because of uncertainties and lack of data, the amount of consumed fuel and chemical reaction emissions are not considered.	
Transportation of Mixed materials within the site	GLO: Truck-trailer, Euro 5, 34 - 40t gross weight / 27t payload capacity (with SCR)	A4	0.05	km
	REF: Diesel mix at refinery	A4	121	kg
Stabilization	Customized process	A5	---	---
	REF: Diesel mix at refinery	A5	3.06E004	kg

*GLO: Global
*REF: Reference

In this project, it is notable to highlight the collaboration with local companies in Köping and neighboring areas. Cementa is a company located in Köping, that acted as the supplier for the cement component (BASE) required for the stabilization of the port. Swecom, based in Öxeslösund, also provided the slag material (GGBS-Merit) for the project. The project also involved partnering with Jakobi Group in Landskrona, which supplied activated carbon (AquaSorb CS).

In this study, two EPDs are used for covering the A1 stage for two raw materials. An environmental product declaration (EPD) serves as a report that presents information regarding the environmental impact of a particular product or material. The foundation of an EPD lies in an LCA that takes into consideration all the environmental factors associated with the product or material, from its initial raw material extraction to its eventual disposal or recycling. EPDs are voluntary documents primarily generated by manufacturers, and they are commonly utilized by experts and engineers to facilitate comparisons of the key environmental impacts among different products [20].

In this study, one of the EPDs is related to slag (GGBS) [21] and the other one is for activated carbon [22]. The chosen EPD for the slag is exactly related to the used slag in the base case (Merit -GGBS- from Swecem) and by consultation with the Peab supervisor the closest option to the used product in the base case was selected for activated carbon. In both EPDs, stages A1-A3 are covered: extraction of raw material, transportation to the factory, and production stage. In this work, these final products are raw materials for the Köping project, which need to be transported to the project site (A2 stage of the stabilized port project). Declared unit in these EPDs are 1 tonne of each finished product, so the claimed number for each environmental impact category need to be scaled to the exact consumed amount of that product. This procedure is shown in Tables 5 and 6.

2.2.6 Environmental Impact Categories

Environmental impact categories are specific areas or aspects of the environment that are assessed during an environmental assessment for example by the LCA method. These categories encompass various environmental factors, such as greenhouse gas emissions, energy consumption, water usage, air pollution, land use, resource depletion, and waste generation. Each category represents a different aspect of the environmental impact associated with a product, a process, or a project. By considering these impact categories, researchers and experts can understand the potential environmental effects, prioritize areas for improvement, and make decisions to minimize the overall environmental footprint [3].

Among all environmental impact categories GWP, AP, EP, and ODP have been selected by Peab to be investigated in this project. The corresponding data to these four categories extracted from the available EPDs for slag and activated carbon are shown in Tables 5 and 6.

Table 5: The values of Environmental Impact Categories for Slag

Slag		
Indicator	**Unit**	**A1-A3**
Global Warming Potential (GWP)	kg CO_2 eq.	4.07E+01
Acidification Potential (AP)	kg SO_2 eq.	2.06E-01
Eutrophication Potential (EP)	kg Phosphate eq.	2.39E-03
Ozone Layer Depletion Potential (ODP)	kg CFC 11 eq.	4.11E-13
Applicable for 1 tonne		

Table 6: The values of Environmental Impact Categories for Activated Carbon

Activated Carbon		
Indicator	**Unit**	**A1-A3**
Global Warming Potential (GWP)	kg CO_2 eq.	1.98E-01
Acidification Potential (AP)	kg SO_2 eq.	3.84E-02
Eutrophication Potential (EP)	kg Phosphate eq.	6.50E-05
Ozone Layer Depletion Potential (ODP)	kg CFC 11 eq.	1.21E-13
Applicable for 1 tonne		

Table 7 shows the procedure of calculating the value of four environmental impact categories for different mixtures of slag and cement.

Table 7: The procedure of calculating values of environmental impact categories for different mixtures of slag and cement

	Slag/ Tonne		
Environmental Impact Categories	**Slag 60% & Cement 40%**	**Slag 70% & Cement 30%**	**Slag 80% & Cement 20%**
	9 343.5	10 734.3	12 573.5
GWP	4.07E+01 × 9 343.5	4.07E+01× 10 734.3	4.07E+01 × 12 573.5
Acidification Potential	2.06E-01 × 9 343.5	2.06E-01 × 10 734.3	2.06E-01 × 12 573.5
Eutrophication Potential	2.39E-03 × 9 343.5	2.39E-03 × 10 734.3	2.39E-03 × 12 573.5
ODP	4.11E-13 × 9 343.5	4.11E-13 × 10 734.3	4.11E-13 × 12 573.5

As the consumed amount of activated carbon is constant in the base case and all eight proposed scenarios, the final effect for four intended environmental impact categories is calculated by the following approach in Table 8.

Table 8: The procedure of calculating values of environmental impact categories for consumed activated carbon

Environmental Impact Categories	**Activated Carbon/ Tonne**
	7 74.3
GWP	1.98E-01× 774.3
Acidification Potential	3.84E-02 × 774.3
Eutrophication Potential	6.50E-05 × 774.3
ODP	1.21E-13 × 774.3

2.2.7 Normalization and Weighting Method

Normalization is the process of establishing reference values or benchmarks against which the environmental impacts can be compared. It allows for a comparison of different impact categories and provides a relative perspective on the significance of various environmental impacts. By normalizing the data, the relative importance of different environmental indicators can be interpreted deeper and prioritize areas for improvement. Normalization factors are typically derived from data on global or regional environmental burdens and are used to scale the impact scores to a common reference point [23].

Weighting factors, on the other hand, are used to assign relative importance or significance to different impact categories. They reflect preferences regarding the relative importance of different environmental impacts. Weighting factors help to aggregate impacts across different categories to calculate an overall environmental impact score. However, it is important to note weighting factors are subjective and dependent on value judgments made during the assessment process [23].

Normalization and weighting factors play an important role in LCA by enhancing the meaningfulness and relevance of assessment results. These factors provide a framework for comparing environmental impacts and assist in identifying areas that require attention for environmental improvement. Incorporating societal preferences, normalization and weighting factors enable decision-makers to make informed choices. They facilitate a comprehensive evaluation of the environmental impact of different alternatives, aiding in the identification of areas for potential improvement and optimization [23].

The "CML 2016, excl biogenic carbon" method is adopted in this study for both normalization and weighting, providing an approach for evaluating environmental impacts. The CML 2016, excl biogenic carbon method is a widely used approach in LCA for normalization and weighting. Developed by the Institute of Environmental Sciences (CML) at Leiden University, this method establishes reference values (normalization) and assigns relative importance (weighting) to environmental impacts. Normalization involves comparing impacts to benchmark data, while weighting factors reflect societal preferences. The CML2016 method excludes biogenic carbon emissions to prevent double-counting and focuses on significant impacts like resource depletion and climate change from fossil fuel combustion [24].

2.3 Life Cycle Cost (LCC)

Another field of work investigated in this study, is calculating Life Cycle Cost (LCC) of the case study. As stages under investigation in this work are limited to A1, A2, A3, A4, and A5, only the initial cost is relevant. Initial cost refers to the total expenses incurred at the beginning of a project or investment. It includes all the costs associated with the project or assets's planning, design, acquisition, and setup. These costs include purchasing equipment or materials, hiring labor, obtaining permits or licenses, and any other expenses directly related to the project's initiation [25]. The initial costs considered in this study are costs for purchasing material, hiring machinery and workmanship payment.

In order to assess the initial cost of the project, relevant information was gathered from Peab, including details on the machinery types used, the number and positions of the labor force, and the total duration of their involvement. As financial information is generally confidential, data collection involved reaching out to supplier companies to obtain pricing details for the materials used in the project. Similarly, rental fees for the machinery were obtained by contacting the respective companies for the daily rates of each machine. To estimate personnel costs, average salary ranges for each position in Peab during the period of 2022-2023 were suggested by Peab's supervisor and utilized. These steps were taken to ensure an accurate assessment of the initial cost while maintaining confidentiality of specific financial details.

2.3.1 Cost of Machinery

To facilitate the project's operation, two distinct types of machines were utilized. The Hitachi Vacker Neuson machinery played a role in the initial step, excavating sediment from the sea. In the subsequent stage, the stabilization process was carried out using a stabilization machine. Detailed information on both machine types can be found in the Table 9. These machines successfully executed the project, contributing to its overall progress and completion. It is worth mentioning that cost of consumed fuel for excavation and stabilization process is included in the rental fees for machineries.

Table 9: Information about machineries

Machinery				
Item	**Model**	**Cost/ (SEK/day)**	**No. of Machines**	**Total work days**
Excavation Machine	Hitachi Vacker Neuson	5 242.00	1	75
Stabilization Machine	Volvo	7 300.00	1	220

2.3.2 Cost of Material

The project currently used three different materials from various suppliers: cement, slag, and activated carbon. Cost information for cement types I, II, and III is essential for analyzing proposed scenarios. These details can be found in Table 10, providing an overview of the required materials and associated costs. It should be noted that the cost of transportation from the factory suppliers to the project site is included in the below prices.

Table 10: Information about materials

Material			
Material	**Type of Material**	**Supplier Company**	**Cost/ (SEK/ tonne)**
Cement	BASE (type I)	Cementa	956.34
Cement	type II	Cementa	1 042.36
Cement	type III	Cementa	1 184.04
Slag (GGBS)	Merit	Swecem	176.59
Activated Carbon	AquaSorb CS	Jakobi Group	18.28

2.3.3 Cost of Workmanship

Table 11 provides an overview of the labor force involved in various project stages, showcasing their respective roles, positions, and monthly salaries. The diverse workforce with their specific responsibilities played a crucial role in the successful execution of the project.

Table 11: Information about Labor Force

Workmanship			
Item	**No. of personnel**	**Work time/ month**	**Fee/ SEK**
Worker (Excavation)	3	4	30 000.00
Worker (Stabilization)	3	10	30 000.00
Project Manager (Exc.)	1	4	60 000.00
Project Manager (Sta.)	1	10	60 000.00
Site Manager (Exc.)	1	4	55 000.00
Site Manager (Sta.)	1	10	55 000.00
Labor Leader (Exc.)	1	4	40 000.00
Labor Leader (Sta.)	1	10	40 000.00

2.4 Integration of LCA and LCC

In addition to analyzing the current situation, this study aims to identify the optimal scenario that considers both LCA and LCC. To achieve this, LCA and LCC were integrated using the Single-Point Rate (SPR) method. The SPR method calculates results by considering a specific data point or rate, without accounting for the potential variability or multiple scenarios that might exist [11]. In this study, SPR employs weighting factors to determine the relative importance of LCA and LCC in relation to each other. For applying this method three options were investigated to assess the impact of different weighting factors on the final results. The considered options for SPR calculations are presented in Table 12, providing insights into the various scenarios examined in this analysis.

Table 12: Weighting factors for different options

Options	**Weighting factors**	
	LCA	**LCC**
Option 1	50 %	50 %
Option 2	60 %	40 %
Option 3	40 %	60 %

3 Results and Discussion

This chapter presents both the results and the corresponding discussion, which are divided into three sections. The first section (section 3.1) offers an overview of the potential environmental impact results, encompassing findings obtained from GaBi (LCA for Experts) and Excel calculations. Section 3.2 presents the results of the economic analysis, followed by section 3.3, which highlights the optimal scenario achieved through the integration of LCA and LCC. This section includes the results of the SPR calculations, providing insights into the optimum scenario identified through the assessment of environmental and economic factors. By incorporating both results and discussion, this chapter presents a comprehensive analysis of the study's findings, facilitating a deeper understanding of the environmental and economic implications of the project.

3.1 Life Cycle Assessment (LCA)

In this study, the LCA results are presented in two distinct sub-sections. Firstly, the LCA results for the base case are discussed, providing an analysis of the environmental impacts across stages A1 to A5. These impacts are assessed based on four key environmental impact categories: Global Warming Potential (GWP), Acidification Potential (AP), Eutrophication Potential (EP), and Ozone Layer Depletion Potential (ODP). Additionally, the study delves into the results of eight proposed scenarios, further expanding the understanding of the environmental impacts associated with different scenarios.

3.1.1 Present Situation (base case)

Table 13 provides a breakdown of the results from the LCA study conducted for the Köping stabilized port project. This table presents detailed information on the various stages of the project, offering insights into the environmental impacts associated with each stage.

Table 13: LCA results for the base case

Environmental Impact Categories/ Stages	A1-A3	A4	A5	A1-A5
CML2001 - Aug. 2016, Acidification Potential (AP)/ kg SO_2 eq.	8.02E+03	1.06E+00	5.19E+01	8.07E+03
CML2001 - Aug. 2016, Eutrophication Potential (EP)/ kg Phosphate eq.	9.53E+02	2.71E-01	1.05E+01	9.64E+02
CML2001 - Aug. 2016, Global Warming Potential (GWP 100 years), excl biogenic carbon/ kg CO_2 eq.	4.43E+06	4.22E+02	1.48E+04	4.45E+06
CML2001 - Aug. 2016, Ozone Layer Depletion Potential (ODP)/ kg R11 eq.	3.84E+06	4.34E-11	1.10E-08	3.84E+06

Table 14 illustrates the contribution of each material to the overall environmental impact within each category. This representation provides an understanding of the relative significance of different materials regarding their environmental impact. It is evident that cement has the most impact across all four categories, clearly demonstrating its dominant role in influencing environmental outcomes compared to other materials.

Table 14: Material contribution to the overall potential environmental impact

A1			
Environmental Impact Categories/ Materials	**Cement**	**Slag**	**Activated Carbon**
CML2001 - Aug. 2016, Acidification Potential (AP)/ kg SO_2 eq.	**5.43E+03**	2.21E+03	2.97E+01
CML2001 - Aug. 2016, Eutrophication Potential (EP)/ kg Phosphate eq.	**8.40E+02**	2.57E+01	5.03E-02
CML2001 - Aug. 2016, Global Warming Potential (GWP 100 years), excl biogenic carbon/ kg CO_2 eq.	**3.84E+06**	4.37E+05	1.53E+02
CML2001 - Aug. 2016, Ozone Layer Depletion Potential (ODP)/ kg R11 eq.	**3.84E+06**	4.41E-09	9.37E-11

3.1.2 Proposed Scenarios

The analysis of various proposed scenarios in terms of LCA has culminated in the consolidation of all results within Table 15. This table serves as a repository of valuable information, showcasing the environmental performance and impacts associated with each scenario.

Table 15: LCA results for proposed scenarios

Scenario	Environmental Impact Category	A1-A3	A1-A5
Scenario 1 (type I-slag 60% & cement 40%)	Acidification Potential (AP)/ kg SO_2 eq.	7.77E+03	7.83E+03
	Eutrophication Potential (EP)/ kg Phosphate eq.	1.17E+03	1.18E+03
	Global Warming Potential (GWP 100 years), excl biogenic carbon/ kg CO_2 eq.	5.14E+06	5.16E+06
	Ozone Layer Depletion Potential (ODP)/ kg R11 eq.	5.41E-06	5.43E-06
Scenario 2 (type I-slag 80% & cement 20%)	Acidification Potential (AP)/ kg SO_2 eq.	6.28E+03	6.33E+03
	Eutrophication Potential (EP)/ kg Phosphate eq.	6.35E+02	6.45E+02
	Global Warming Potential (GWP 100 years), excl biogenic carbon/ kg CO_2 eq.	6.35E+02	3.01E+06
	Ozone Layer Depletion Potential (ODP)/ kg R11 eq.	2.51E-06	2.55E-06
Scenario 3 (type II-slag 70% & cement 30%)	Acidification Potential (AP)/ kg SO_2 eq.	6.94E+03	7.00E+03
	Eutrophication Potential (EP)/ kg Phosphate eq.	7.87E+02	7.97E+02
	Global Warming Potential (GWP 100 years), excl biogenic carbon/ kg CO_2 eq.	3.65E+06	3.66E+06
	Ozone Layer Depletion Potential (ODP)/ kg R11 eq.	3.95E-06	3.97E-06
Scenario 4 (type II-slag 60% & cement 40%)	Acidification Potential (AP)/ kg SO_2 eq.	7.94E+03	7.99E+03
	Eutrophication Potential (EP)/ kg Phosphate eq.	9.77E+02	9.88E+02
	Global Warming Potential (GWP 100 years), excl biogenic carbon/ kg CO_2 eq.	4.50E+06	4.52E+06
	Ozone Layer Depletion Potential (ODP)/ kg R11 eq.	5.14E-06	5.15E-06

Scenario 5 (type II-slag 80% & cement 20%)	Acidification Potential (AP)/ kg SO_2 eq.	5.63E+03	3.06E+03
	Eutrophication Potential (EP)/ kg Phosphate eq.	5.45E+02	5.15E+02
	Global Warming Potential (GWP 100 years), excl biogenic carbon/ kg CO_2 eq.	2.54E+06	2.03E+06
	Ozone Layer Depletion Potential (ODP)/ kg R11 eq.	2.40E-06	2.39E-06
Scenario 6 (type III-slag 70% & cement 30%)	Acidification Potential (AP)/ kg SO_2 eq.	4.81E+03	4.87E+03
	Eutrophication Potential (EP)/ kg Phosphate eq.	4.62E+02	4.73E+02
	Global Warming Potential (GWP 100 years), excl biogenic carbon/ kg CO_2 eq.	2.05E+06	2.07E+06
	Ozone Layer Depletion Potential (ODP)/ kg R11 eq.	3.75E-06	3.76E-06
Scenario 7 (type III-slag 60% & cement 40%)	Acidification Potential (AP)/ kg SO_2 eq.	5.16E+03	5.21E+03
	Eutrophication Potential (EP)/ kg Phosphate eq.	5.54E+02	5.65E+02
	Global Warming Potential (GWP 100 years), excl biogenic carbon/ kg CO_2 eq.	2.42E+06	2.44E+06
	Ozone Layer Depletion Potential (ODP)/ kg R11 eq.	4.87E-06	4.88E-06
Scenario 8 (type III-slag 80% & cement 20%)	Acidification Potential (AP)/ kg SO_2 eq.	4.35E+03	4.41E+03
	Eutrophication Potential (EP)/ kg Phosphate eq.	3.40E+02	3.51E+02
	Global Warming Potential (GWP 100 years), excl biogenic carbon/ kg CO_2 eq.	1.56E+06	1.58E+06
	Ozone Layer Depletion Potential (ODP)/ kg R11 eq.	2.26E-06	2.27E-06

To delve deeper into the proposed scenarios and make meaningful comparisons with the present situation, a meticulous investigation was conducted to determine how each scenario performs in relation to the desired life cycle impact categories. This detailed analysis provides valuable insights into the performance of each scenario across different categories, enabling a comprehensive understanding of their respective strengths and weaknesses.

Figure 5 illustrates the impact of each Scenario on the environment, specifically focusing on the "Acidification Potential" environmental impact category. Scenario 8 demonstrates the best performance in this category, with a total of 4.41E+03 [kg SO_2 eq.] across stages A1-A5 of the project. Following closely, Scenario 6 occupies the second-best position with a total of 4.87E+03 [kg SO_2 eq.], followed by Scenario 5 with a value of 5.68E+03 [kg SO_2 eq.]. These findings shed light on the relative performance of each scenario in terms of their impact on Acidification Potential, providing insights for further analysis and decision-making processes.

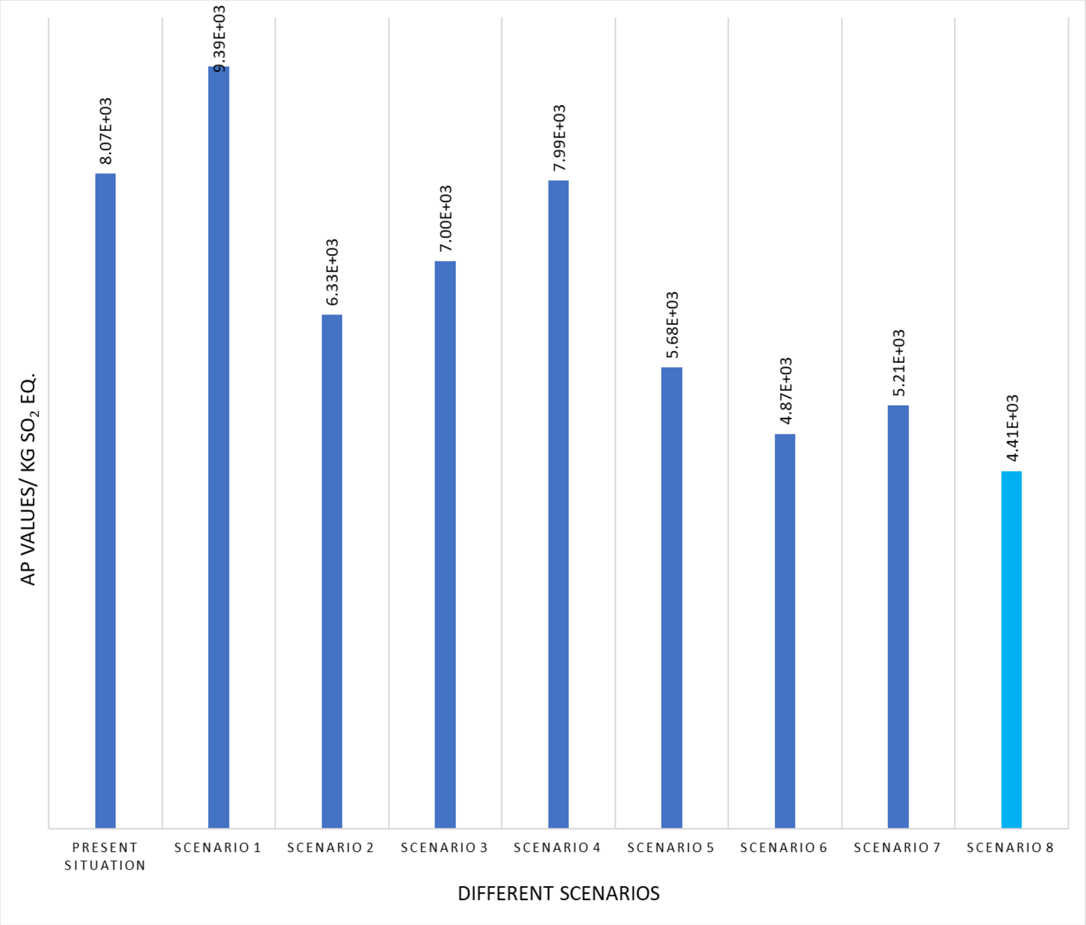

Figure 5: AP comparison between different scenarios/ kg SO_2 eq.

Figure 6 showcases the results of the investigation and comparison of the Eutrophication Potential impact category among all proposed scenarios. This category was assessed to gain insights into the environmental impacts associated with each scenario. By visualizing the results, EP across different scenarios was compared. The findings presented in Figure 7 provide a contribution to the overall understanding of the environmental implications of the proposed scenarios.

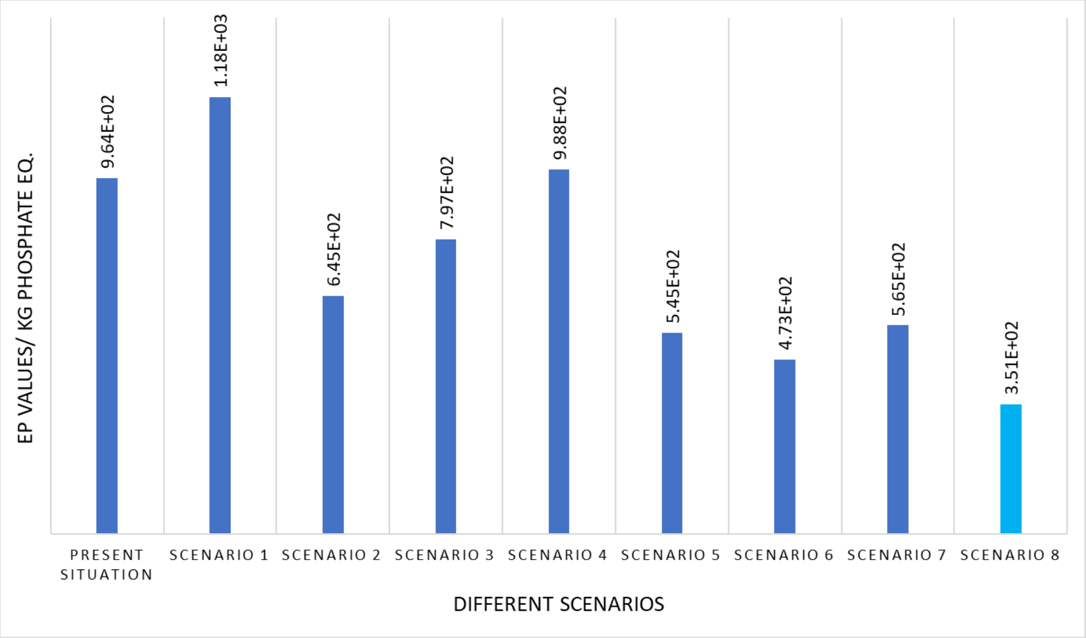

Figure 6: EP comparison between different scenarios/ kg Phosphate eq.

Within the EP impact category, Scenario 8 stands out as the top performer among all proposed scenarios, showcasing a notable difference compared to Scenario 1 and 4, as well as the present situation. On the other hand, among all proposed scenarios and the present situation, Scenario 1 (cement type I - slag 60% & cement 40%) exhibits the poorest performance, with a value of 1.18E+03 [kg Phosphate eq.] for the investigated phases. These findings highlight the contrasting outcomes in terms of Eutrophication Potential, emphasizing the significance of scenario selection in minimizing environmental impacts within this category.

The subsequent category analyzed in both the present situation and proposed scenarios is the GWP. Once again, Scenario 8 emerges as the top performer, replicating its success in the EP environmental impact category. Scenario 8 is defined by specific attributes, featuring cement type III, with a binder composition of 80% slag and 20% cement. This study confirms that this configuration has a capacity to mitigate global warming potential, emphasizing its notable role in advancing the project's sustainability objectives.

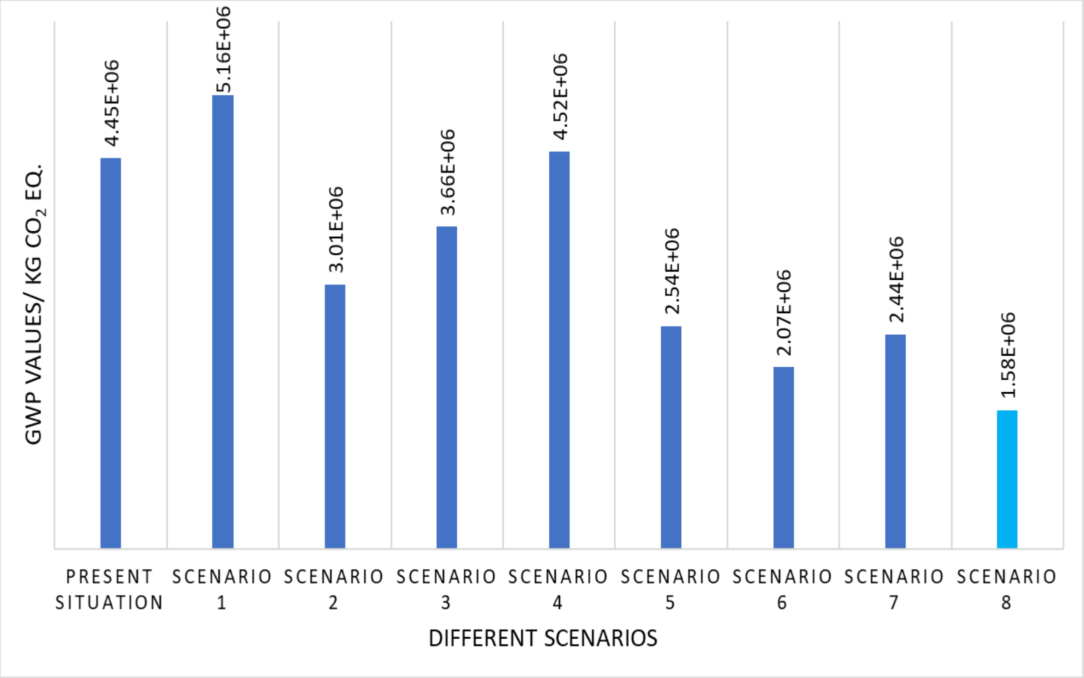

Figure 7: GWP comparison between different scenarios/ kg CO_2 eq.

Within the Global Warming Potential category, Scenarios 6 and 5 stand out as better performers after Scenario 8. Scenario 6, associated with cement type III featuring 70% slag and 30% cement, exhibits the best environmental results in GWP category after Scenario 8. Scenario 5, linked to cement type II with a combination of 80% slag and 20% cement, also stands in the third level. Despite the higher amount of cement used in Scenario 6 compared to Scenario 5, the crucial factor contributing to the reduction of the GWP environmental impact lies in its cement type. The composition of cement type III in Scenario 6 plays a pivotal role in achieving more favorable GWP results, showcasing the significance of careful material selection in influencing environmental outcomes. This finding underscores the importance of considering not only the quantity but also the specific characteristics of materials utilized in the scenarios for optimizing sustainability performance.

Consistently, this trend is observed across the previously investigated environmental impact categories, where Scenario 8 maintains its top-ranking position, followed by Scenario 6 in second place, and Scenario 5 in third place. The pivotal difference lies in the specific cement type utilized in each scenario, with Scenario 8 and 6 employing cement type III with 20% and 30% of the binder weight, respectively, while Scenario 5 critically relies on cement type II, accounting for 20% of the binder weight. These results emphasize that, even when cement weights are closely comparable, its quality and type exert a more significant influence on environmental impacts compared to its weight.

The Ozone Layer Depletion Potential emerged as the final environmental impact category investigated in this study, solidifying Scenario 8 as the best performer in Life Cycle Assessment for the fourth time. Figure 8 reveals a remarkably tight competition, with Scenario 8 taking the lead, followed closely by Scenario 5 in second place and Scenario 2 securing the third position. These results underscore the environmental performance of Scenario 8 and highlight the close competition among the top-performing scenarios in mitigating ozone layer depletion potential.

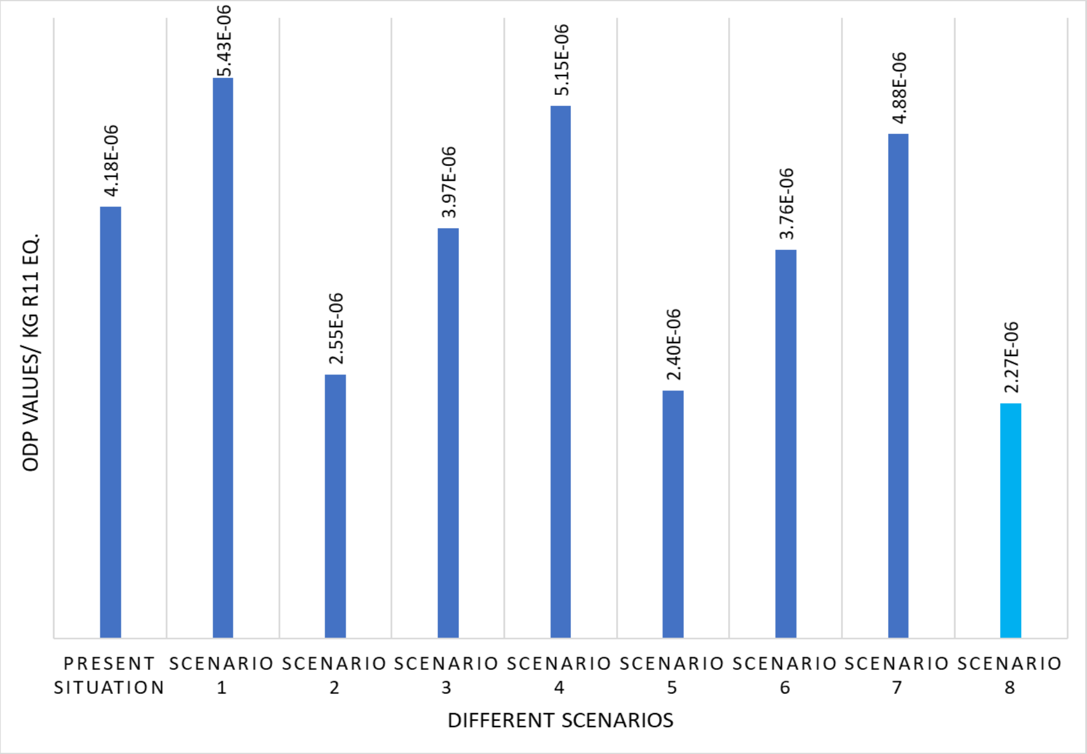

Figure 8: ODP comparison between different scenarios/ kg R11 eq.

By findings from this part of study, it becomes evident that cement holds a central role as the most influential contributor in the ODP category. All three scenarios that outperformed the others in this category share a common trait: they employ the lowest amount of cement in the binder mixture, comprising merely 20% of the binder weight. This finding accentuates the significance of judiciously managing cement utilization to optimize environmental outcomes in terms of ODP.

Another interesting result arising from this section of the study is the impact of “cement quality” on the potential depletion of Ozone layer. A clear and consistent trend is unveiled, wherein the improvement in cement quality from type I to type III directly correlates with a reduction in its negative impact on the ODP category. This significant correlation underscores the crucial role of using more environmental-friendly cement, particularly type III, in curbing adverse effects on the Ozone layer.

By analysing LCA results from these four investigated environmental categories, it is obvious that there is a similar trend between four different categories. By looking at three scenarios within each distinct cement type, always scenario with higher amount of cement in the binder mixture (40%) has the highest environmental impact which is followed by scenario with 30% of cement in binder mixture and finally scenario with 20% used cement in the mixture composition.

Figure 9 presents one of the most important results of this study. This figure showcases the "Weighted and Normalized" LCA results, integrating the findings from the four previously discussed impact categories, utilizing the CML 2016, excl biogenic method. Through this approach, figure 10 offers a perspective on the total environmental impact of each scenario within four investigated categories. This representation is instrumental in understanding the overall environmental performance of the scenarios.

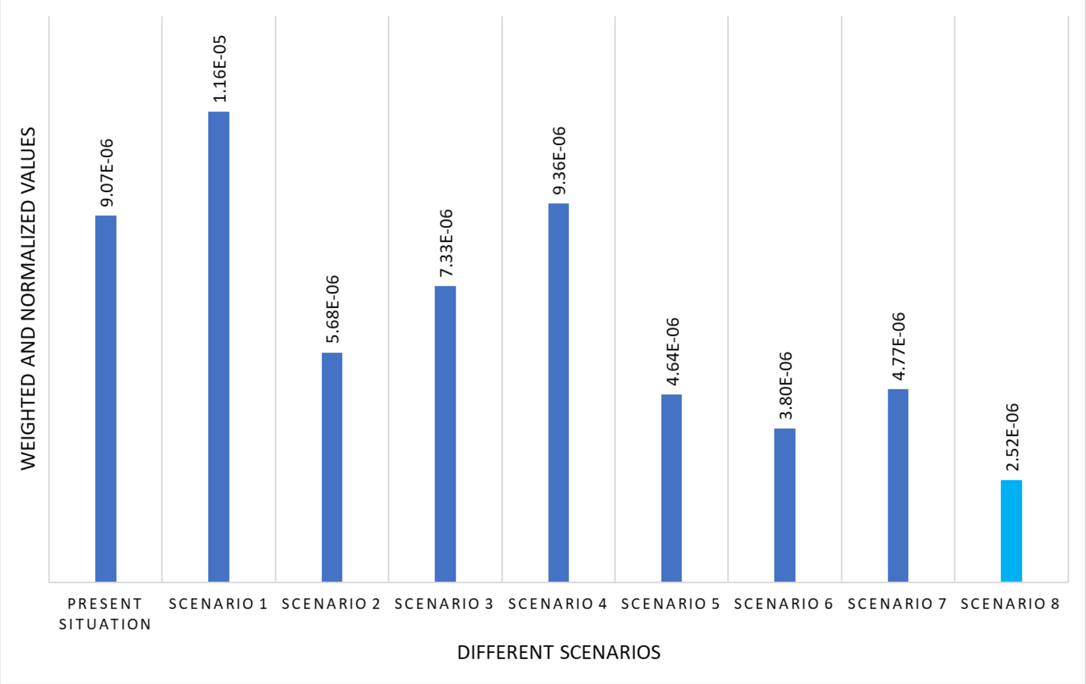

Figure 9: Weighted and Normalized results

Throughout examining each environmental impact category, Scenario 8 consistently demonstrated superior performance compared to the other scenarios. Now, delving into the normalized and weighted results, the inference drawn is clear: Scenario 8 emerges as the best performer from the LCA perspective, significantly outperforming the other scenarios. This comprehensive analysis solidifies Scenario 8 as the most favorable choice regarding its environmental impact, underscoring its contribution to the project's overall sustainability goals. The notable margin of its performance compared to other scenarios, along with the careful composition of each material, underscores the critical importance of prudent material selection.

3.2 Life Cycle Costing (LCC)

The study encompassed an LCC analysis for both the present situation of the project and all proposed scenarios. This in-depth analysis calculated the initial cost of each scenario. While the cost of "workforce" and "machinery" remained identical between the present situation and proposed scenarios, amounting to 3.43 MSEK and 1.99 MSEK, respectively. The cost of materials exhibited variations across scenarios. Figure 10 visually depicts the material costs for each scenario, while Figure 12 provides an overview of the total initial cost consumed and required for the Köping port stabilization project, inclusive of the proposed scenarios. For detailed cost breakdowns, the appendix A offers further numerical insights.

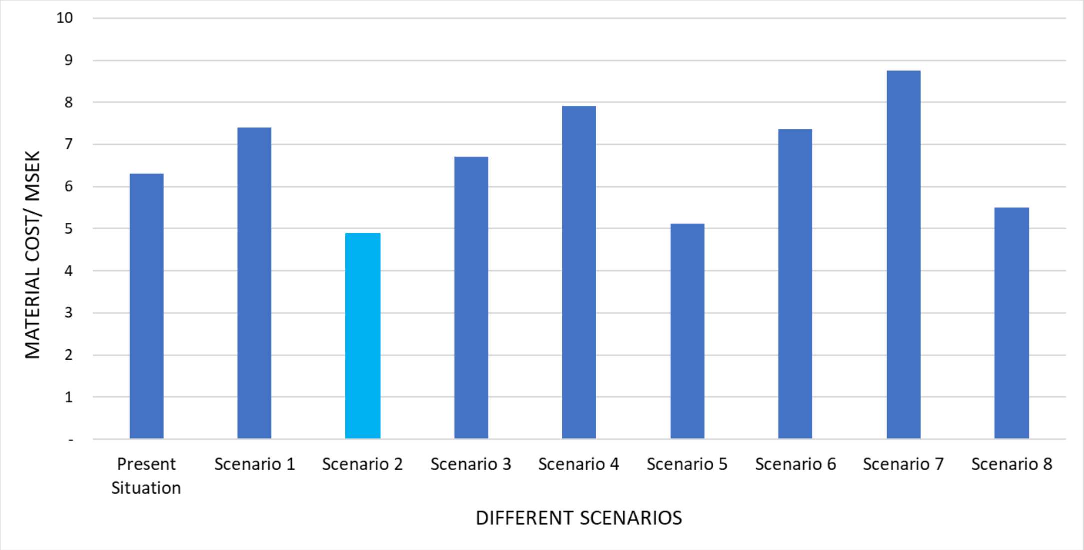

Figure 10: Material cost in present and proposed scenarios/ MSEK

Scenario 5 stands out among the scenarios examined with the lowest material cost of 5.11 MSEK, closely followed by Scenario 2 with a total material cost of 4.87 MSEK. Ranking third in this cost comparison is Scenario 8, with a material cost of 5.50 MSEK. This study shows that cement continues to play a pivotal role, not only in the LCA aspect but also in the LCC aspect. Scenarios that utilize the lowest amount of ccment (20% of binder weight) exhibit the best cost performance compared to others, with a slight increase in this amount corresponding to the improvement in cement quality (type I, type II, type III). It is worth mentioning that the total material cost for the present situation amounts to approximately 6.30 MSEK.

The project's overall initial cost is estimated at approximately 11.73 MSEK, yet it notably decreases to 10.34 MSEK in Scenario 2, showcasing a cost-saving potential around 10% in this particular scenario.

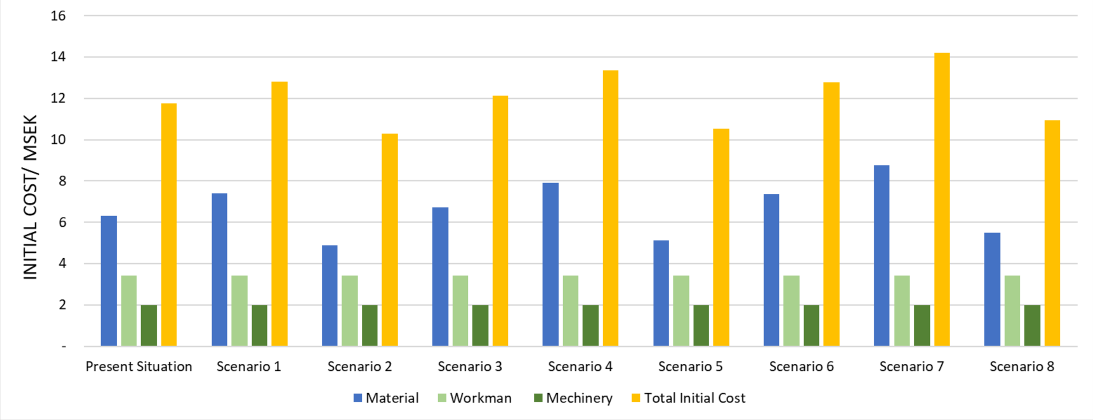

Figure 11: Initial cost in present and proposed scenarios/ MSEK

3.3 Integration of LCA and LCC

SPR calculations were conducted to identify the optimal scenario. This integration has been performed by considering different weights for both LCA and LCC. Table 16 presents different weighting factors and the minimum SPR values as well as their corresponding scenario, providing insights into the optimal scenario based on the combined assessment of environmental and economic factors.

Table 16: Minimum SPR values and corresponding scenario

Options	Weighting factors		**Minimum SPR value**	**Related Scenario**
	LCA	**LCC**		
Option 1	50%	50%	5.15E+06	Scenario 2/ cement type I – slag 80% & cement 20%
Option 2	60%	40%	4.12E+06	Scenario 2/ cement type I – slag 80% & cement 20%
Option 3	40%	60%	6.18E+06	Scenario 2/ cement type I – slag 80% & cement 20%

The results presented in the above table highlight that Scenario 2 exhibits the lowest SPR value across all three options. This scenario comprises cement type I, with a binder mixture of 80% slag and 20% cement. The study confirms that cement plays the most pivotal role among all materials in terms of both economic and environmental aspects. As we progressed through different stages of the study, the expectation was that scenarios with lower amounts of cement would be the most favorable. However, given the significant influence of economic factors on the overall project, Scenario 2 resulted in the lowest impact when it comes to economical and environmental consideration. With cement type I, which is the most cost-effective among various types, Scenario 2 struck the ideal balance between environmental impact and economic feasibility, making it the optimal choice for the Köping port stabilization project

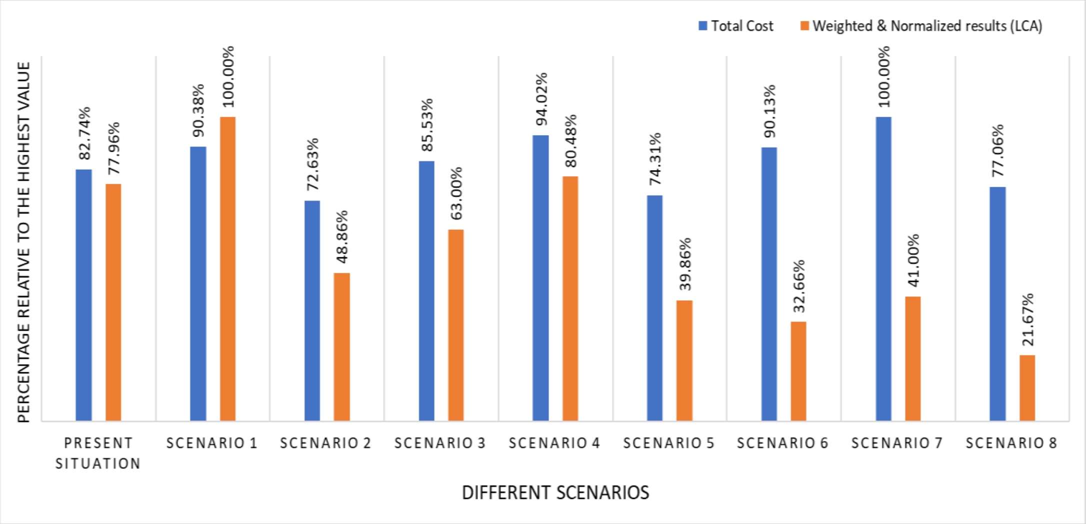

Figure 12: Integration of "weighted and normalized" results with LCC results in one graph

An interesting perspective that can be explored in the results is the integration of "normalized and weighted" outcomes from LCA with the total Life Cycle Cost in a single graph, as shown in Figure 12. In the base case, cement type I with a slag-cement portion distribution of 70%-30% is utilized. In Scenario 6, cement type III is employed with the same portion distribution in the binder mixture. Analyzing the total cost for each scenario, it becomes evident that the difference between them is merely around 1 MSEK (Million Swedish Krona). However, when considering the total environmental impact, the present scenario exhibits approximately 2.38 times higher impact compared to Scenario 6.

Furthermore, an intriguing comparison between the base case and Scenario 8 can be made. In Scenario 8, using cement type III with a slag-cement portion of 80%-20% results in a total Life Cycle Cost estimated to be around 1 MSEK less than the present situation. Moreover, the total environmental impact of Scenario 8 is about 3.59 times lower than the present scenario.

While these cost and environmental impact comparisons provide valuable insights, thoroughly investigating the proposed scenarios' mechanical properties is essential. Ensuring that the desired requirements of the project can be met is a crucial aspect that warrants careful examination. This assessment will determine the feasibility and viability of implementing the alternative scenarios in practical applications, considering both the economic and environmental considerations.

In this study, integrating LCA results with the LCC in one graph enables an evaluation of different scenarios by considering cost-effectiveness and environmental sustainability at the same time. It becomes apparent that by optimizing the binder mixture and cement types used in the construction process, reductions in environmental impact can be achieved without incurring substantial cost differences. This integrated analysis is instrumental in advancing sustainable practices in construction projects, aligning them with environmental goals while maintaining economic feasibility.

4 Conclusion

This study aimed to address two key questions: the first being the environmental impact of the Köping port after stabilization by Peab and the overall cost incurred by Peab from the A1 stage to the completion of the construction phase. The second question focused on identifying the most optimal solution for stabilizing the port, comparing the present situation to other potential options in terms of both Life Cycle Assessment (LCA) and Life Cycle Costing (LCC).

An study was conducted to answer the first question, beginning with the construction process modeling of the project in GaBi (LCA for Experts) using the most appropriate and relevant materials. This process involved calculating the project´s environmental impacts and presenting the results through detailed and illustrative graphs in previous chapters. The initial cost calculation for the project were divided into three parts: material, machinery, and workforce costs. The findings highlighted that material costs accounted for the highest portion of the total cost.

Addressing the second question, eight scenarios were proposed, varying cement types and material proportions in the binder mixture. These scenarios underwent comprehensive assessments in terms of both LCA and LCC, mirroring the approach taken for the base case.

In the LCA analysis, Scenario 8 consistently demonstrated the best performance across the four selected environmental impact categories (AP, EP, GWP, ODP). This scenario, comprising cement type III, slag 80%, and cement 20%, underscored the critical role of material selection in reducing a project's environmental impact. By comparing "Normalized and Weighted results," it became evident that cement with the highest quality (type III) among Scenarios 6, 7, and 8 exhibited lower potential environmental impacts. The comparison between Scenario 5 and 6 confirmed this trend, as the higher cement quantity in Scenario 6 resulted in lower environmental impacts compared to Scenario 5, with the key differentiator being the cement type (type III versus type II).

Analyzing the initial cost for the eight proposed scenarios revealed that cement cost had the most significant impact on the total cost. Consequently, scenarios with lower amounts of cement in their material composition (Scenario 2, 5, and 8) showcased better results from the LCC perspective. Among these three cost-efficient scenarios, Scenario 2, with cement type I, emerged as the best performer, while Scenario 8, with cement type III, exhibited the highest cost impact. Thus, it was evident that improving the quality of cement resulted in increased project costs.

In the final decision-analysis step, integrating LCA and LCC demonstrated that cost played a decisive role in outweighing the project´s environmental impact. Across all three weighting factors for LCA and LCC, Scenario 2, with the lowest cost among the alternatives, emerged as the best performer. With cement type I, 80% slag, and 20% cement of the total binder weight, Scenario 2 proved to be the optimal choice for the Köping port stabilization project, balancing environmental sustainability and cost-effectiveness. These findings underscore the importance of thoughtful material selection and strategic decision-making in achieving the most favourable outcomes in construction projects.

5 Limitations and Future Study

This study was conducted based on a stabilization project undertaken by Peab company as a contractor in Köping port, Sweden. To ensure the accuracy of the data used in the LCA and LCC, information was validated using data provided by the company and supplemented with data from academic studies. However, it should be noted that the conclusions drawn from the LCC study may not be universally applicable to other cities or projects, as the study relied on project-specific data for the Köping stabilized port.

One limitation in this work pertains to uncertainties in the A3 stage of the LCA study. During this stage, all materials (cement, slag, activated carbon, and sediment) were mixed, and some fuel was consumed with machinery. However, this aspect was omitted from the LCA and LCC analyses due to the lack of required data. Additionally, emissions created during the mixing process were acknowledged but could not be included in the study due to the absence of valid chemical data on their type and quantity.

At the study´s outset, Peab requested the investigation of two more environmental impacts, Freshwater Aquatic Ecotoxicity and Marine Aquatic Ecotoxicity. As there was no appropriate data regarding slag and activated carbon in GaBi (LCA for Experts) databases which are used in this study, available Environmental Product Declarations (EPDs) for slag and activated carbon were used to proceed the work. However, after collecting available EPDs for slag and activated carbon, it was discovered that these two categories were not covered in them. Consequently, due to the lack of data, they had to be omitted from the study, and the focus continued on the four remaining environmental impact categories.

Another limitation in this study was the neglect of the amount and type of contaminants present in the excavated sediment from the sea. Although the Stabilization and Solidification process can trap contaminants and prevent their release into the seawater, this aspect was not within the scope of this study. It requires a separate and comprehensive chemical-focused investigation.

It is essential to conduct further validation and experimentation to examine the material properties of the proposed stabilization mixture. A laboratory study may be necessary to test whether this mixture effectively meets the mechanical and technical requirements of the project. Such additional research would solidify the feasibility and viability of Scenario 2 as the ideal solution for the Köping port stabilization project.

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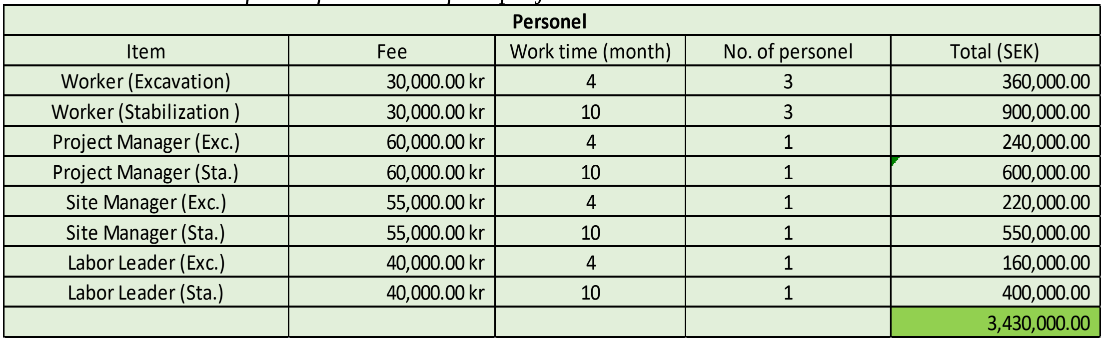
7 Appendix A

7.1 Values of Life Cycle Cost (LCC)

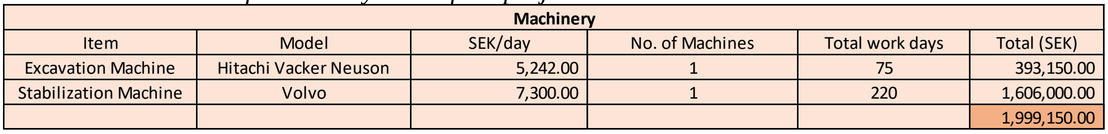
Three below tables are showcasing preliminary calculations in different parts of LCC. The cost related to workmanship and machinery were constant within base case and proposed scenarios, while variation of material cost in different scenarios led to different initial cost which are representing in Table 3.

Table 1: Calculation of Workforce Cost of the project



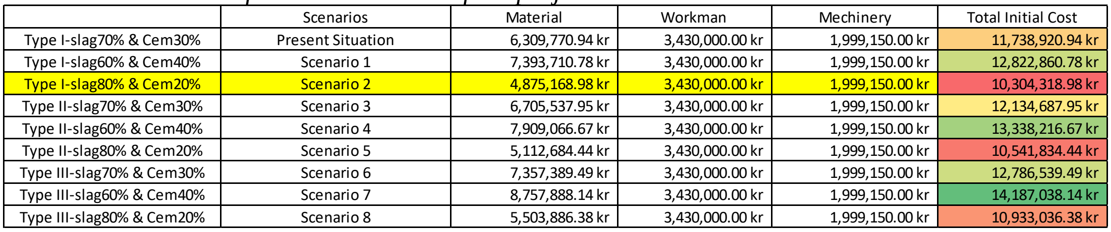
Personel				
Item	Fee	Work time (month)	No. of personel	Total (SEK)
Worker (Excavation)	30,000.00 kr	4	3	360,000.00
Worker (Stabilization)	30,000.00 kr	10	3	900,000.00
Project Manager (Exc.)	60,000.00 kr	4	1	240,000.00
Project Manager (Sta.)	60,000.00 kr	10	1	600,000.00
Site Manager (Exc.)	55,000.00 kr	4	1	220,000.00
Site Manager (Sta.)	55,000.00 kr	10	1	550,000.00
Labor Leader (Exc.)	40,000.00 kr	4	1	160,000.00
Labor Leader (Sta.)	40,000.00 kr	10	1	400,000.00
				3,430,000.00

Table 2: Calculation of Machinery Cost of the project



Machinery					
Item	Model	SEK/day	No. of Machines	Total work days	Total (SEK)
Excavation Machine	Hitachi Vacker Neuson	5,242.00	1	75	393,150.00
Stabilization Machine	Volvo	7,300.00	1	220	1,606,000.00
					1,999,150.00

Table 3: Calculation of Total Initial Cost of the project

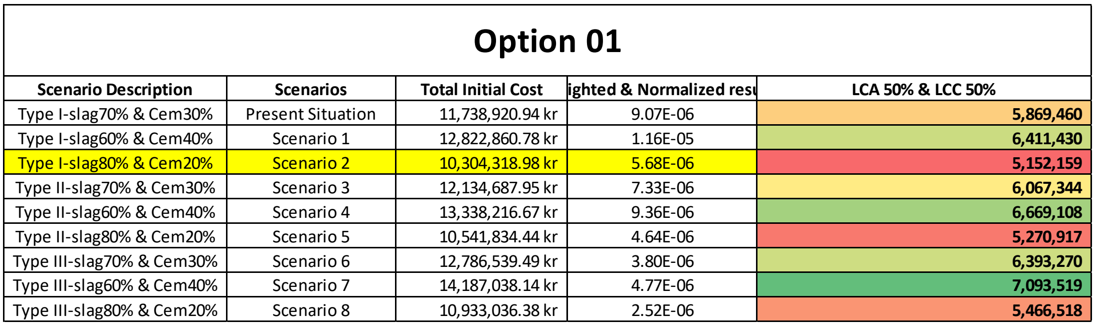


	Scenarios	Material	Workman	Mechinery	Total Initial Cost
Type I-slag70% & Cem30%	Present Situation	6,309,770.94 kr	3,430,000.00 kr	1,999,150.00 kr	11,738,920.94 kr
Type I-slag60% & Cem40%	Scenario 1	7,393,710.78 kr	3,430,000.00 kr	1,999,150.00 kr	12,822,860.78 kr
Type I-slag80% & Cem20%	Scenario 2	4,875,168.98 kr	3,430,000.00 kr	1,999,150.00 kr	10,304,318.98 kr
Type II-slag70% & Cem30%	Scenario 3	6,705,537.95 kr	3,430,000.00 kr	1,999,150.00 kr	12,134,687.95 kr
Type II-slag60% & Cem40%	Scenario 4	7,909,066.67 kr	3,430,000.00 kr	1,999,150.00 kr	13,338,216.67 kr
Type II-slag80% & Cem20%	Scenario 5	5,112,684.44 kr	3,430,000.00 kr	1,999,150.00 kr	10,541,834.44 kr
Type III-slag70% & Cem30%	Scenario 6	7,357,389.49 kr	3,430,000.00 kr	1,999,150.00 kr	12,786,539.49 kr
Type III-slag60% & Cem40%	Scenario 7	8,757,888.14 kr	3,430,000.00 kr	1,999,150.00 kr	14,187,038.14 kr
Type III-slag80% & Cem20%	Scenario 8	5,503,886.38 kr	3,430,000.00 kr	1,999,150.00 kr	10,933,036.38 kr

7.2 Values of integration of LCA and LCC

Table 4, 5, and 6 are representing different options which are applied on both LCA and LCC results to get Single-Point Rate values.

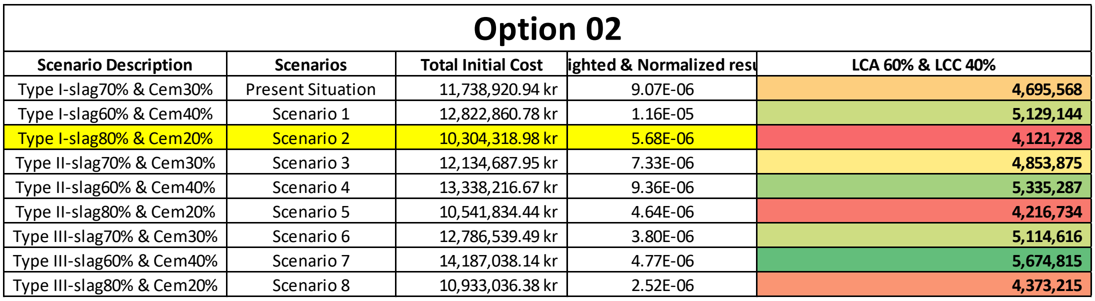
Table 4: Calculated values of SPR for each scenario, LCA (50%), LCC (50%)



Option 01

Scenario Description	Scenarios	Total Initial Cost	ighted & Normalized resu	LCA 50% & LCC 50%
Type I-slag70% & Cem30%	Present Situation	11,738,920.94 kr	9.07E-06	**5,869,460**
Type I-slag60% & Cem40%	Scenario 1	12,822,860.78 kr	1.16E-05	**6,411,430**
Type I-slag80% & Cem20%	Scenario 2	10,304,318.98 kr	5.68E-06	**5,152,159**
Type II-slag70% & Cem30%	Scenario 3	12,134,687.95 kr	7.33E-06	**6,067,344**
Type II-slag60% & Cem40%	Scenario 4	13,338,216.67 kr	9.36E-06	**6,669,108**
Type II-slag80% & Cem20%	Scenario 5	10,541,834.44 kr	4.64E-06	**5,270,917**
Type III-slag70% & Cem30%	Scenario 6	12,786,539.49 kr	3.80E-06	**6,393,270**
Type III-slag60% & Cem40%	Scenario 7	14,187,038.14 kr	4.77E-06	**7,093,519**
Type III-slag80% & Cem20%	Scenario 8	10,933,036.38 kr	2.52E-06	**5,466,518**

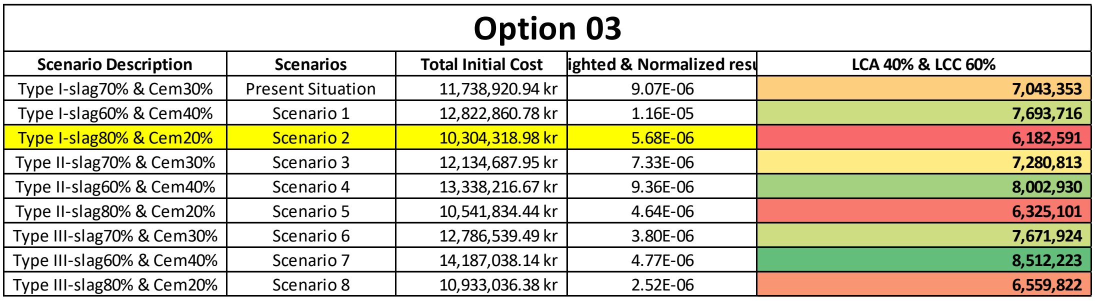
Table 5: Calculated values of SPR for each scenario, LCA (60%), LCC (40%)



Option 02

Scenario Description	Scenarios	Total Initial Cost	ighted & Normalized resu	LCA 60% & LCC 40%
Type I-slag70% & Cem30%	Present Situation	11,738,920.94 kr	9.07E-06	**4,695,568**
Type I-slag60% & Cem40%	Scenario 1	12,822,860.78 kr	1.16E-05	**5,129,144**
Type I-slag80% & Cem20%	Scenario 2	10,304,318.98 kr	5.68E-06	**4,121,728**
Type II-slag70% & Cem30%	Scenario 3	12,134,687.95 kr	7.33E-06	**4,853,875**
Type II-slag60% & Cem40%	Scenario 4	13,338,216.67 kr	9.36E-06	**5,335,287**
Type II-slag80% & Cem20%	Scenario 5	10,541,834.44 kr	4.64E-06	**4,216,734**
Type III-slag70% & Cem30%	Scenario 6	12,786,539.49 kr	3.80E-06	**5,114,616**
Type III-slag60% & Cem40%	Scenario 7	14,187,038.14 kr	4.77E-06	**5,674,815**
Type III-slag80% & Cem20%	Scenario 8	10,933,036.38 kr	2.52E-06	**4,373,215**

Table 6: Calculated values of SPR for each scenario, LCA (40%), LCC (60%)



Option 03

Scenario Description	Scenarios	Total Initial Cost	ighted & Normalized resu	LCA 40% & LCC 60%
Type I-slag70% & Cem30%	Present Situation	11,738,920.94 kr	9.07E-06	**7,043,353**
Type I-slag60% & Cem40%	Scenario 1	12,822,860.78 kr	1.16E-05	**7,693,716**
Type I-slag80% & Cem20%	Scenario 2	10,304,318.98 kr	5.68E-06	**6,182,591**
Type II-slag70% & Cem30%	Scenario 3	12,134,687.95 kr	7.33E-06	**7,280,813**
Type II-slag60% & Cem40%	Scenario 4	13,338,216.67 kr	9.36E-06	**8,002,930**
Type II-slag80% & Cem20%	Scenario 5	10,541,834.44 kr	4.64E-06	**6,325,101**
Type III-slag70% & Cem30%	Scenario 6	12,786,539.49 kr	3.80E-06	**7,671,924**
Type III-slag60% & Cem40%	Scenario 7	14,187,038.14 kr	4.77E-06	**8,512,223**
Type III-slag80% & Cem20%	Scenario 8	10,933,036.38 kr	2.52E-06	**6,559,822**

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