EVALUATION OF SOLIDIFICATION/ STABILIZATION TECHNOLOGY PERFORMANCE BY COMBINING ECONOMIC AND ENVIRONMENTAL IMPACTS ASSESSMENT FOR A PORT IN SWEDEN

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KEYWORDS

Life cycle assessment, Economic analysis, Stabilization, Solidification, Cement mixtures

ABSTRACT

The importance of reducing environmental impacts has gained speed in the contemporary global context. Stabilization/Solidification (S/S) has become a practical method for handling polluted dredged sediments to make them usable as a construction material. This study aims to evaluate the environmental and economic impacts of a 48,586 m^2 port, with stabilized dredged sediment, by focusing on the production and construction stages in Sweden. It encompasses eight distinct scenarios that are proposed based on cement types and binder mixtures. Environmental impact categories, including Global Warming Potential (GWP), Acidification Potential (AP), Eutrophication Potential (EP), and Ozone Depletion Potential (ODP), were assessed. Life Cycle Assessment (LCA) modeling was carried out in the software LCA for Experts (GaBi). The study also incorporates Life Cycle Cost (LCC) calculations to be integrated with LCA results, using the Single-Point Rate (SPR) method to aid decision analysis. The results show that the optimal scenario features cement type I with a 20% cement and 80% slag binder mixture. This choice demonstrated a nearly 29% reduction in environmental impacts and approximately 1.5 MSEK lower initial costs compared to the base case which is cement type I with a 30% cement and 70% slag binder mixture. These results highlight the potential for environmentally responsible and cost-effective decision-making in infrastructure projects through an integrated LCA and LCC approach.

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1. INTRODUCTION

The global emphasis on reducing environmental impacts, as evidenced by the Sustainable Development Goals (SDGs) and the Paris Agreement, underscores the significance of sectors like construction and real estate in advancing sustainable practices [1]. Life Cycle Assessment (LCA) has emerged as a methodology for evaluating the environmental impacts of construction projects [2]. LCA calculation tools like LCA for Experts (GaBi) facilitate analysis of environmental impacts across various life cycle stages of construction materials and processes. Life Cycle Cost (LCC) calculations are performed for evaluating the economic consequences of an item or system, by summing all costs incurred during their life span [2].

Stabilization and Solidification techniques, commonly employed in managing hazardous waste materials, offer practical solutions for transforming contaminants into stable forms suitable for disposal or reuse [3]. In the context of dredging operations, where substantial volumes of sediment require management, stabilization/solidification methods have been proven to effectively manage contaminated dredged sediments [4]. This study aims to evaluate the environmental and economic impacts associated with a port project, located in Gothenburg, Sweden, both for the present situation and also other possible alternatives. Then, eight different scenarios are proposed. By assessing both environmental and economic aspects, the study seeks to provide insights and recommendations for informed decision analysis regarding the project and its alternatives [5].

2. METHOD

The Methodology section of this paper encompasses three key steps: LCA, LCC, and Decision Analysis. LCA involves defining the assessment unit, establishing system boundaries, collecting data on raw material inputs, energy consumption, emissions, and assessing environmental impacts such as greenhouse gas emissions [6,7]. LCC analysis identifies cost components, including capital and operational expenses, using historical data and expert opinions [6,7]. Decision Analysis utilizes evaluation criteria aligned with research objectives and applies the Single-Point Rate (SPR) method to rank alternative scenarios based on environmental and economic impacts [6,7].

2.1. Case study and proposed scenarios

The case study focuses on the Köping Port Deepening and Harbor Basin Expansion Project, an integral component of the Mälarprojektet. The project involves deepening and widening the fairway and harbor basin, stabilizing and solidifying dredged sediments, and creating an industrial zone spanning 48,586 m2 [8]. Key tasks include constructing access roads, establishing temporary quays, implementing drainage systems, and noise barriers to ensure smooth operations [8]. The project aims to efficiently utilize stabilized dredged sediment and mitigate environmental impact [8]. Figure 1 provides an overview of the project location, emphasizing its proximity to major road connections and neighboring industrial operations.

Figure 1: Overview of the project location

This study investigates various alternative scenarios within the Köping Port project to assess their environmental and economic impacts. These scenarios, analyzed through LCA and LCC, aim to understand the project's sustainability implications and identify optimal options. Each scenario, distinguished by different types and proportions of cement and slag in the binder mixture, is outlined in Tables 1 and 2 for easy comparison, providing insights into their environmental and cost considerations.

Table 1: 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 2: Amount of each material in different portions 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)

The LCA methodology applied in this study encompasses defining the assessment unit, establishing system boundaries, and collecting data on environmental impacts, focusing on the Köping Port project's production and construction phases. The LCA evaluation considers various life cycle stages, including raw material extraction, transportation, construction processes, and product delivery to the project site. Employing LCA for Experts (GaBi) software, version 10.6.1, enables analysis, utilizing databases such as Ecoinvent and Sphera to assess environmental impacts across different stages. Additionally, the study utilizes Environmental Product Declarations (EPDs) for slag and activated carbon, covering stages A1-A3, to provide detailed insights into the environmental impact of raw materials. Environmental impact categories such as Global Warming Potential (GWP), Acidification Potential (AP), Eutrophication Potential (EP), and Ozone Layer Depletion Potential (ODP) are investigated. The normalization and weighting methods employed, particularly the CML 2016, excluding biogenic carbon, allow for comparisons and prioritization of environmental impacts [9]. Overall, this approach facilitates a thorough assessment of the Köping Port project's environmental impacts and identifies areas for improvement to promote sustainable development.

2.3. Life Cycle Cost (LCC)

This study examines the initial cost of the Köping Port project, which is related to the production and construction stages [10]. Required data were gathered from Peab (a construction company) and suppliers, including machinery rental fees and material costs as well as reasonable estimations for personnel expenses. Tables 3, 4, and 5 detail machinery types, material costs, and labor force involvement, respectively, providing insights into project finances.

Table 3: 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

Table 4: 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

Table 5: 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

The study aims to determine the optimal scenario by integrating LCA and LCC, using the SPR method [6,7]. This method, depicted in Table 6, utilizes weighting factors to gauge the relative importance of LCA and LCC. By considering three options for SPR calculations, the study assesses different scenarios to provide insights into the project's environmental and economic impact viability.

Table 6: 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

3.1. Life Cycle Assessment (LCA)

Figure 2 shows the environmental impact of each scenario, focusing on Acidification Potential (AP). Among the scenarios examined, scenario 8 emerges with the lowest impact with 4.41E+03 [kg SO_2 eq.], followed by scenario 6 with 4.87E+03 [kg SO_2 eq.], and scenario 5 with 5.68E+03 [kg SO_2 eq.]. Scenario 1 illustrates the highest AP with 9.39E+03 [kg SO_2 eq.]. The observed differences underscore the importance of considering alternative materials and cement formulations in mitigating the environmental impacts of construction activities. Scenario 8, characterized by cement type III with a higher ratio of slag, demonstrates the potential benefits of utilizing sustainable materials in cement production.

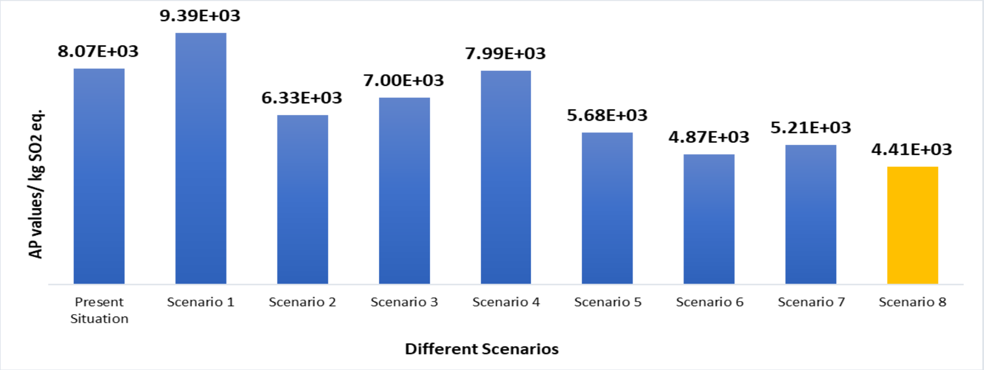

Figure 2: Acidification Potential comparison between different scenarios [kg SO_2 eq.]

Figure 3 presents the Eutrophication Potential (EP) across scenarios. Similar to AP results, scenario 8 has the lowest results with 3.51E+02 [kg Phosphate eq.], with a notable difference from scenario 1 with 1.18E+03. This highlights the importance of scenario selection in minimizing EP. The analysis highlights the potential of sustainable cement formulations (type and percentage) in mitigating environmental impact and promoting eco-friendly construction practices.

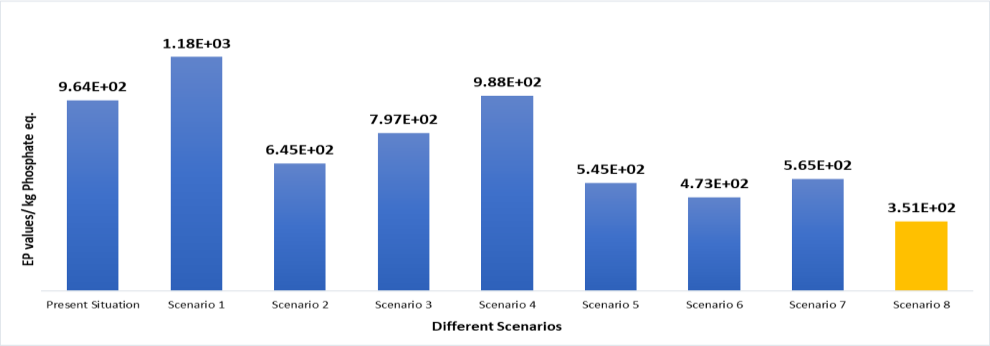

Figure 3: Eutrophication Potential comparison between different scenarios [kg Phosphate eq.]

The subsequent category analyzed in both the present situation and proposed scenarios is the Global Warming Potential (GWP). Once again, scenario 8 shows the best results, this time in the GWP environmental impact category. Scenario 8, defined by specific attributes including cement type III with a binder composition of 80% slag and 20% cement, demonstrates a notable capacity to mitigate GWP, emphasizing its pivotal role in advancing sustainability objectives. Following scenario 8, scenarios 6 and 5 stand out as better performers within the GWP category. Scenario 6, associated with cement type III featuring 70% slag and 30% cement, exhibits the best GWP results after scenario 8. Despite using a higher amount of cement compared to scenario 5, scenario 6's advantageous GWP results can be attributed to its cement type III composition, underscoring the significance of careful material selection in influencing environmental outcomes. This trend is consistent across previously investigated environmental impact categories, where scenario 8 maintains the lowest impact, 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, highlighting that even when cement weights are comparable, its quality and type exert a more significant influence on environmental impacts.

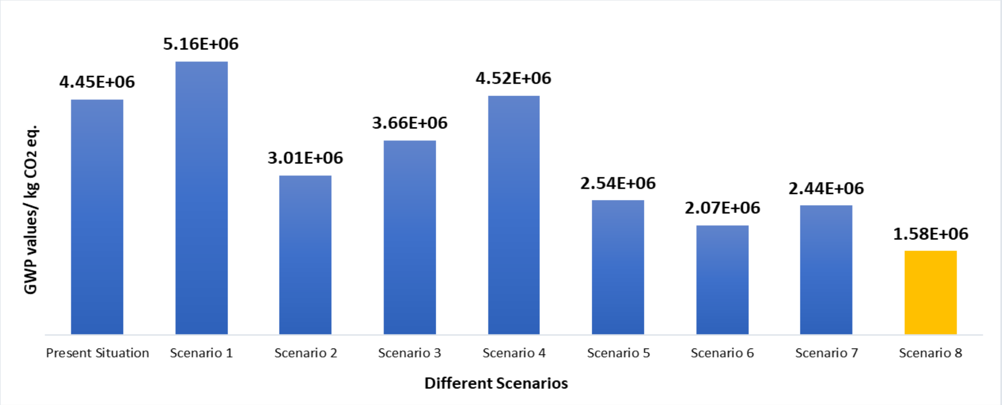

Figure 4: Global Warming Potential comparison between different scenarios [kg CO_2 eq.]

In Figure 5, Ozone Depletion Potential (ODP) was investigated, confirming scenario 8 as the top performer in the life cycle assessment for the fourth time. scenario 8 leads, followed closely by scenario 5 in second place and scenario 2 in third, highlighting their environmental performance in mitigating ozone layer depletion. The analysis of the ODP category in Figure 5 reveals the role of cement in influencing environmental outcomes. scenarios with lower cement content, specifically comprising 20% of the binder weight, consistently outperform others, highlighting the importance of cement management in optimizing ODP. Moreover, the study elucidates a clear correlation between cement quality and ODP, with the transition from type I to type III cement demonstrating a reduction in negative environmental impact, particularly on the Ozone layer depletion potential.

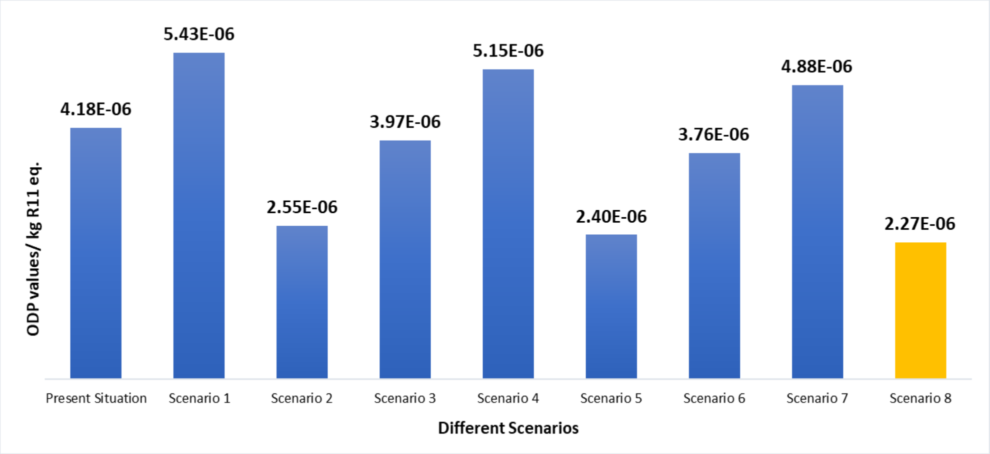

Figure 5: Ozone Depletion Potential comparison between different scenarios [kg R11 eq.]

Figure 6 presents weighted and normalized LCA results, integrating findings from various environmental impact categories. Scenario 8 consistently emerges as the top performer across these categories, demonstrating superior environmental performance compared to others. This reinforces scenario 8's significance in achieving sustainability goals and underscores the critical role of material selection in mitigating environmental impacts.

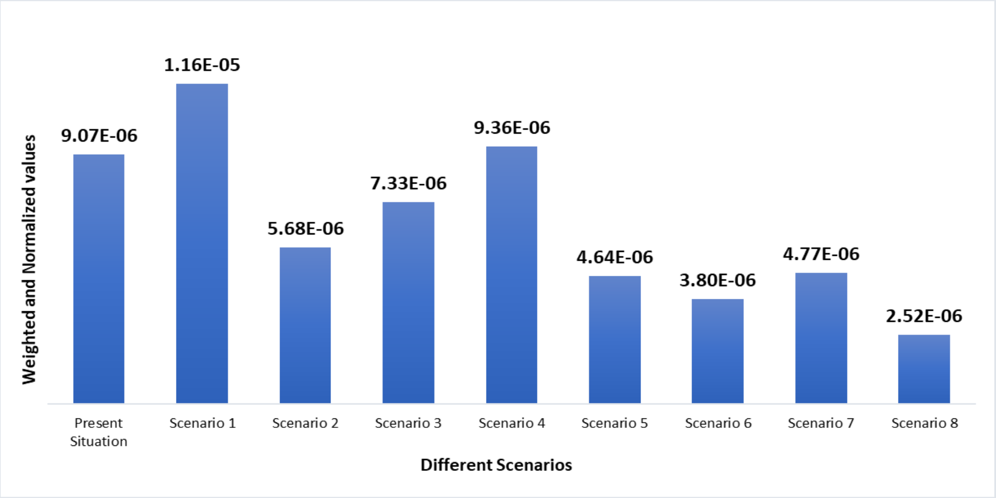

Figure 6: Weighted and Normalized results

3.2. Life Cycle Costing (LCC)

The total initial cost for the project is around 11.73 MSEK. However, it reduced to 10.34 MSEK in scenario 2, indicating a potential cost reduction of approximately 10% in this specific scenario.

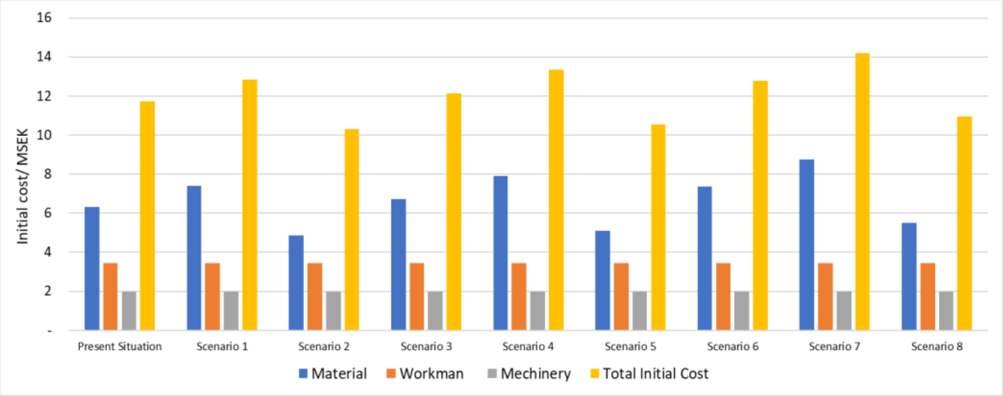

Figure 7: Initial cost in present and proposed scenarios [MSEK]

3.3. Integration of LCA and LCC

SPR calculations integrate LCA and LCC weights to determine the optimal scenario. Table 7 displays weighting factors and minimum SPR values, offering insights into the combined assessment of environmental and economic factors to identify the optimal scenario. The below table shows scenario 2, with the lowest SRP value, features cement type I with an 80% slag and 20% cement binder mixture. Despite expectations favoring scenarios with less cement, scenario 2, with the most cost-effective cement type, strikes the ideal balance between environmental impact and economic feasibility, making it the optimal choice for the Köping port stabilization project.

Table 7: Lowest SPR values and corresponding scenario

Options	Weighting factors		**Lowest 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%

Figure 8 shows the LCA and LCC results for all scenarios. Despite a marginal cost difference of about 1 MSEK, scenario 6 shows approximately 2.38 times lower environmental impact compared to the base case. Similarly, scenario 8, employing cement type III with an 80%-20% slag-cement distribution, yields a cost saving of around 1 MSEK compared to the base case, with a 3.59 times lower environmental impact.

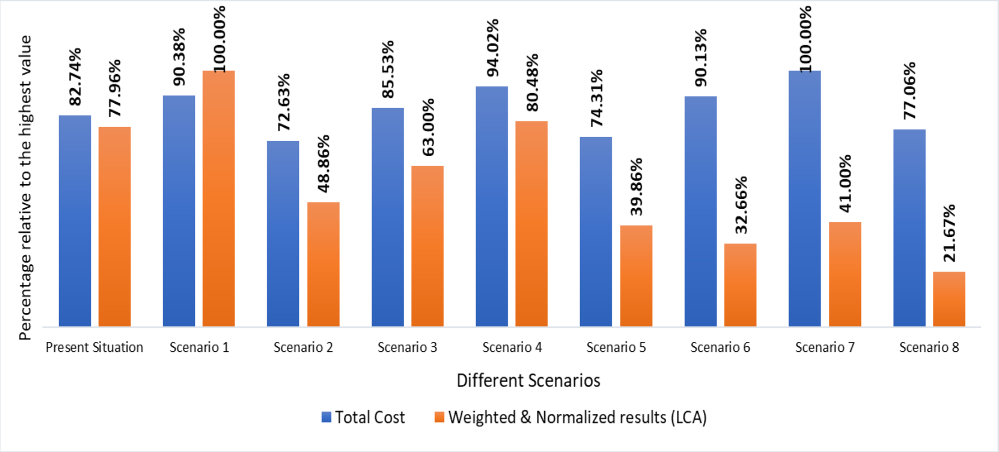

Figure 8: Integration of weighted and normalized LCA results with LCC results

4. LIMITATIONS AND FURTHER STUDY

Data validation from the industrial lab and academic sources ensured project-specific insights, although limitations included uncertainties in the A3 stage of the LCA study and emissions due to data constraints. Additional environmental impacts like Freshwater Aquatic Ecotoxicity and Marine Aquatic Ecotoxicity were not fully explored due to data limitations, while contaminants in excavated sediment were not addressed. Further validation and experimentation are recommended to assess the mechanical properties of the proposed stabilization mixture, ensuring its feasibility for this project.

5. CONCLUSIONS

This study aimed to investigate the environmental and economic impacts during the stabilization of a port project in Sweden, as well as to identify the most optimal stabilization solution. By considering material, machinery, and workforce costs, it was found that material costs dominated the project's total expenses. Eight scenarios through varying cement types and proportions were analyzed and the results revealed that scenario 8 (cement type III, 80% slag & 20% cement) consistently performed best across selected environmental impact categories.

Based on the LCA analysis, scenario 8, featuring cement type III, resulted in a lower environmental impact, emphasizing the importance of material selection in reducing the project's environmental impact. Moreover, while cement cost significantly influenced total expenses, scenarios with lower cement content, like scenario 2 (cement type I, 80% slag & 20% cement), emerged as the best option from the cost perspective. Integrating LCA and LCC highlighted the decisive role of cost in decision-making, ultimately identifying scenario 2 as the optimal choice, and striking a balance between environmental aspects and cost-effectiveness. These findings emphasize the importance of thoughtful material selection and strategic decision analysis in construction projects.

ACKNOWLEDGEMENT

I am grateful to Peab for their collaboration on this project. Additionally, I appreciate their provision of essential data, such as material content, which significantly contributed to its completion.

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