Preference-Based Decision Support for Quay Wall Assessment

Determining the preferred configuration of structural adjustments using the optimisation method of Preferendus

by

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Preface

As I present this master's thesis, I reflect on this project which has been as challenging as it has been rewarding. My background in mechanical engineering had not previously crossed paths with geotechnical or hydraulic engineering, let alone quay walls and sheet pile walls in particular. These subjects were completely new to me, so I knew it would be a challenging project that I could sink my teeth into. The combination of learning about these completely new subjects combined with a lot of programming - a field I find both challenging and immensely rewarding (if your code works at least) - made it a graduation project I worked on with great enthusiasm. Moreover, I got the chance to carry out this project at construction company BAM, which taught me how to combine the scientific with the operational.

Since I could not have done this on my own, I would firstly like to express my gratidude to my graduation committee. First of all, my sincere thanks to the chair of my committee, Ruud Binnekamp, who not only guided me through several courses of my master Construction Management and Engineering but also introduced me to the Preferendus tool and its potential impact. Secondly, I am grateful to Alfred Roubos, with whom I had interesting discussions about quay wall and sheet pile wall content. Besides, the opportunity you gave me to witness the innovative technique of placing underwater anchors at the Port of Rotterdam was one of the highlights of my graduation project. Thirdly, my thanks to Teun Janssen, who explained the workings of genetic algorithms and their efficient application in my project. Your expertise was very important for my learning process.

I would also like to thank the people at BAM, who were all open for questions during my graduation project. A special mention to my internship supervisor, Maarten de Moel, for your endless patience when I did not understand specific civil engineering or quay wall aspects. In addition, I would also like to thank you for offering me the opportunity to carry out this project at BAM. Secondly, I would like to thank Christian Rasch for the support in geotechnical knowledge, guiding me in the use of D-sheet Piling and PLAXIS 2D. This was crucial for me in developing the tool. Lastly, I extend my thanks to Johan Tuls, whose support in Python scripting and general programming skills were crucial to the success of my project as well.

Finally, I would like to thank my family, friends and girlfriend for their unconditional support throughout my studies. Especially during this graduation process, I could also always turn to you guys when there seemed to be no end in sight, for which I am very grateful.

I hope you enjoy reading my thesis. Hopefully, by the end, you will have learnt how a tool was developed that can determine the preferred configuration of structural adjustments for an existing sheet pile wall!

J.J. Aulbers
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Summary

Currently, the European Commission is focused on shifting freight transport from roads to inland waterways (IWW). To support this transition, the capacity of inland ports should be increased by accommodating larger cargo ships. This expansion requires lowering the water bottom, which will increase the forces exerted on the quay walls. As a result, the existing quays will either have to be reinforced or renewed. To minimise the costs and environmental impact, the chosen option is to reinforce the quay walls by applying structural adjustments. The current approach to find the preferred adjustments is by conducting a variant study. Such study is normally conducted during the preliminary design phase, during which a number of variants are designed from which the stakeholders can then choose the most preferred solution. However, this approach contains several aspects that could be improved. For example, currently a lot of time and money is wasted on initial calculations, as the available information about a specific case is often limited during this design phase. Besides this lack of efficiency, there is a lack of insight in the financial and environmental impact of the considered structural adjustments. It is desirable to know this impact already to gain much insight into possible solutions. Moreover, the preferred configuration of adjustments is currently determined *a-posteriori*, meaning that the preferred solution is chosen from a number of variants instead of directly determining the preferred solution.

The goal of this project is therefore to develop a decision support tool that enables determining the configuration of structural adjustments that contains the highest aggregated preference score of involved stakeholders. This configuration should result in a sheet pile design that, on the one hand, satisfies and extends its lifetime by 50 years, and on the other hand, minimises environmental impact and costs. To implement this, the Preferendus will be applied which uses an *a-priori* design optimisation method that maximises the aggregated stakeholder preference score while satisfying technical constraints. The tool to be developed should enable increased efficiency in sheet pile calculations, provide insight into the financial and environmental impact of all solutions and directly determine the preferred configuration of structural adjustments. It will be made using computational science, by developing a Python script to automate repetitive calculations that integrates with D-Sheet Piling for specific sheet pile calculations. It should only depend on input data, such as sheet pile specifics, geometric specifications, active top loads, anchor usage and soil profiles. Besides, it should be applicable on each existing steel sheet pile and be capable of testing automatically for failure mechanisms. Lastly, it should be able to directly determine the preferred configuration of adjustments, rather than having to select this configuration from a number of variants. Three options are considered to strengthen an existing quay wall, for which the five most potential adjustments are selected. The first option is lowering the active soil stress, by substituting a soil layer for lightweight material BIMS. The second option involves increasing the passive soil stress, for which two adjustments are considered: lowering the pile tip level of a sheet pile and placing a colloidal concrete layer. The third option is to add stability to the sheet pile, which can be achieved by placing anchors above the waterline (AW) or by installing underwater (UW) anchors.

This thesis uses three case studies to test the developed tool, all located in the industrial harbour Loven in Tilburg. It follows the same approach for each case study. Initially it verifies whether a case study requires adjustments to withstand the future water bottom level, identifying the active failure mechanism. Subsequently, it presents the tool's results, highlighting all applicable individual adjustments that meet the design requirements and determining the preferred configuration. The thesis compares this configuration against the new sheet pile scenario in terms of ECI-price, CO2 emissions, and costs. Thereafter, it visualises the results by plotting them on the preference curve of each stakeholder and it verifies the preferred configuration in PLAXIS. Additionally, this thesis presents the results of the sensitivity analysis of each case study as well. This analysis involves varying in the active top loads, corrosion rates and soil parameters. The goal here is to gain insight into possible scenarios that may not require adjustments and to determine which adjustments would be applicable in potential future situations, such as when active top loads or initially assumed corrosion rates increase.

Table 1 presents the main results of the case studies, highlighting the unique preferred configuration for each case and the notable reductions in ECI-price, CO2 emissions, and costs they entail compared to the new sheet pile situation of each case.

Case Study	Failure Mechanism	Preferred Configuration	Reduction vs New Sheet Pile		
			ECI-price	CO2	Costs
Case Study 1	Failure of soil	Extension of sheet pile by: 0.5 m	98%	98%	94%
Case Study 2	Failure of existing anchors	AW Anchors of length: 14.0 m	82%	76%	83%
Case Study 3	Failure of soil	BIMS soil layer of thickness: 0.5 m	95%	95%	91%

Table 1: Summary of Case Studies Results

Table 2 summarises the sensitivity analysis results. The situations in which the top loads are reduced are different for each case study, based on the current top loads of those cases. The future situations include increases in active top loads and initially assumed corrosion rates. For case study 2 it holds that the top load was not increased, indicated by a $*$, as it already contained 350 kPa. The table presents the great potential of improving the soil parameters cohesion c and friction angle ϕ. However, it should be noted that this improvement should apply to every soil layer and is not guaranteed by laboratory tests. It is thus recommended to conduct a follow-up research for this finding. Additionally, the table shows the great potential of placing UW anchors as they are applicable in the future situations of each case study. As applying them is currently still an innovation technique, a follow-up study is also recommended.

Case Study	Situations Requiring No Adjustments	Adjustments Applicable in Future Situations
Case Study 1	1. Reduce sand storage top loads by 24% 2. Improve c and ϕ by 3%	1. Extending sheet pile by 1.0 m 2. Place UW anchors on level 9.5 +m N.A.P.
Case Study 2	1.Place top loads 4.5 metres back 2. Improve c and ϕ by 6%	1. Placing anchors above water of 14.0 m* 2. Place UW anchors on level 9.5 +m N.A.P.*
Case Study 3	1. Reduce container loads by 22% 2. Improve c and ϕ by 3%	1. Adding BIMS as soil layer of 1.5 m thick 2. Place UW anchors on level 9.5 +m N.A.P.

Table 2: Summary of Results Sensitivity Analyses

This thesis first presents conclusions for any structural adjustment considered. It concludes that replacing a soil layer for BIMS has great potential because it is not related to a specific failure mechanism. Secondly, it concludes that extending a sheet pile can mainly be used if the failure mechanism of a sheet pile is the failure of soil leading to an unstable sheet pile wall. Thirdly, it concludes that placing colloidal concrete does not show any potential as structural adjustment if it is added as soil layer at the passive side. Fourthly, it concludes that placing anchors above the waterline can mainly be used if the failure mechanism of a sheet pile is the failure of support mechanisms. However, since all case studies had existing anchors, it does not present a conclusion about the situations where they are missing. Lastly, it concludes that placing underwater anchors has great potential to be used, as it is not related to any specific failure mechanism and is also applicable in possible future situations. Moreover, this thesis presents conclusions about the development of the tool. In general, a tool has been created that is intended to be used during the preliminary design phase, covering all the needs and technical requirements drawn up. In short, it therefore concludes that the development of a decision support tool for existing quay walls has been successful. The tool has demonstrated direct added value, of which the three most valuable aspects are:

- **Increased efficiency**: The tool enabled an increased efficiency in conducting sheet pile calculations. As a result, the tool also increased the efficiency of conducting a variant study of structural adjustments and performing a sensitivity analysis.
- **Financial and environmental impact insights**: Secondly, the tool enabled it to show the environmental and financial impact of all adjustments and combine this with the sheet pile calculations. As a result, this provides not only insight into whether a design that satisfies has been created but also immediately indicates the associated ECI-price, CO2 emissions, and costs.
- **Direct determination of preferred solution**: Lastly, the tool has enabled it to directly determine the preferred configuration of structural adjustments. This eliminates the need to analyse a number of variants afterwards and thus determine the preferred configuration *a-posteriori*.

Contents

1 Introduction

One of the funding instruments the EU currently offers is the Connecting Europe Facility (CEF). Part of this funding is CEF Transport, which is the financing instrument for the implementation of European transport infrastructure policy. It aims to support investments in building new sustainable transport infrastructure across Europe or upgrading existing one. Its primary focus is on projects within the Trans-European Transport Network (TEN-T). These include cross-border projects, projects aimed at removing bottlenecks or bridging missing links. Additionally, it supports other projects such as traffic management systems and the transition to low-carbon fuels [1].

Inland waterways (IWW) are an important part of CEF Transport's focus and require significant improvements. The CEF funding allocated to inland waterway actions account for 1.5 billion euros which is approximately 5.5% of the total budget [1]. Spanning over 37,000 kilometres and connecting numerous cities and industrial regions [2], the European Commission is keen on improving IWW's role in the transport system and especially in its integration into the intermodal logistics chain. This is also because IWW transport is characterized by its reliability, energy efficiency, and capacity for increased exploitation. Its environmental advantages are notable, consuming only 17% of the energy used by road transport and 50% of the energy used by rail transport per km/ton of transported goods [2]. Moreover, it is also safe, particularly for the transportation of dangerous goods, and contributes to reducing congestion on overloaded road networks in densely populated regions.

Because of these environmental and safety advantages, the European Commission aims on shifting freight transport from roads to IWW. One of the projects that is part of this approach, is the project 'Rhombus UPSIDE: Upscaling inland Port infrastructure in Support of modal shift and regional Sustainable Development'. This project received a funding from the CEF Transport budget [3] and aims on improving the IWW connections and the connected infrastructure from the Netherlands to Belgium and Germany. The goal of the project is therefore to enlarge the capacity of six inland ports. Figure 1.1 shows these ports, namely the ports of Stein (1), Roermond (2), Zevenellen (3), Maastricht (4), Venlo (5) and Tilburg (6) [3].

To increase the current capacity of these ports, accommodating larger cargo ships is necessary. This requires significant modifications to some ports, including dredging to lower the water bottom. However, such modifications will increase the forces exerted on the quay walls of the inland ports. Quay walls, essential marine structures positioned between land and water, play a crucial role in the safe and efficient handling of ships. These walls vary in design, primarily serving to securely moor and berth floating vessels [5]. Due to the increased forces, the existing quay walls of those ports are likely insufficient to meet the necessary structural standards. These include stability, strength, and stiffness and are critical for safe and effective operation. Thus, to ensure that the quay walls can withstand the increased forces, structural adjustments will have to be made to the existing quay walls or new quay walls should be placed.

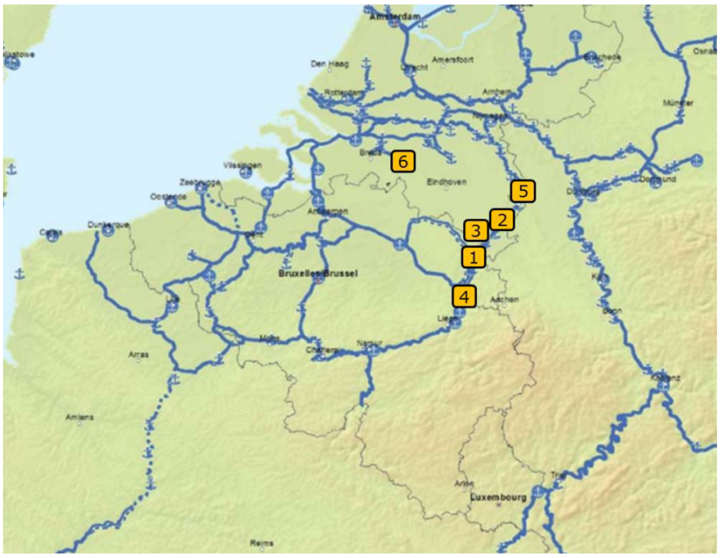


Figure 1.1: Inland ports of project Rhombus UPSIDE [4]

1.1. Involved stakeholders

To arrive at a robust decision on reinforcing or renewing the quay walls, several objectives should be addressed. These objectives arise from various stakeholders that are involved in this project. These stakeholders and their associated interests are as follows:

- **The municipalities of the different ports**: The municipalities prefer to extend the lifetime of the existing quay walls rather than install new quays. This option contains their preference, as it has both financial and environmental advantages. Extending the lifetime of the existing quays is in line with Rijkswaterstaat's Multiannual programme Infrastructure, Spatial planning and Transport (MIRT) program, which is a government investment program for projects and programs in the spatial domain (such as roads and bridges) [6]. The central government is directly financially involved in these projects and programs. As part of MIRT, Rijkswaterstaat developed design principles to circularity on an object level [7]. Figure 1.2 shows these design principles. The first step is to investigate whether it is possible to do nothing about the quay walls and thus whether adjustments can be prevented. However, if calculations show that the design of a quay wall doesn't satisfy when the water bottom is lowered, the principle of value preservation applies.

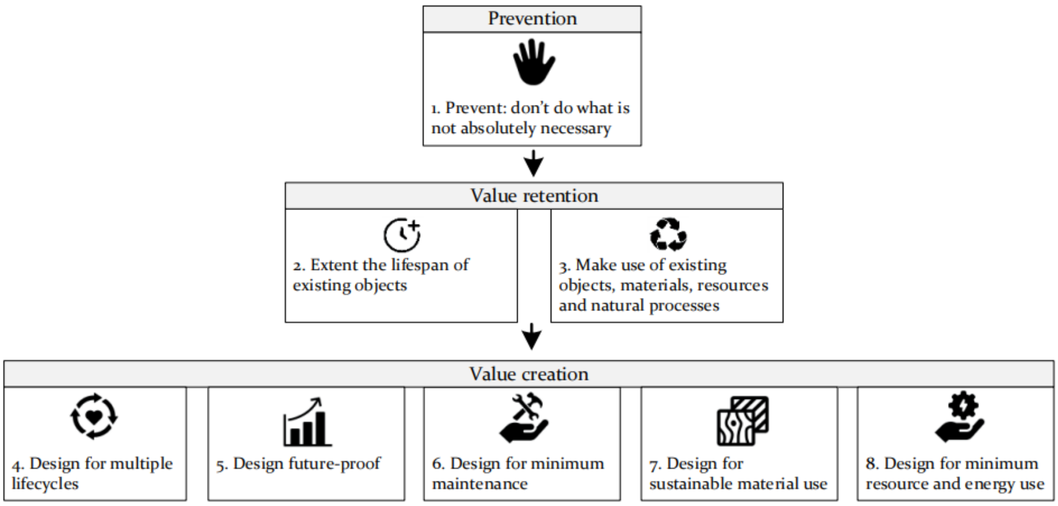


Figure 1.2: Circular design principles of Rijkswaterstaat [7]

- **The European Union**: The EU is involved as well since they are in charge of the CEF Transport budget. This is 'extra' budget made available to contribute to shifting freight transport from roads to IWW. In addition, the EU is also pursuing the goal of value retention, as this is in line with the Paris agreement and the EU's goals set out in the European Green deal and the Fit for 55 package [3].
- **Owner of a quay wall**: The owner of a quay wall is also involved. His interest is that no restrictions are imposed on activities on the quay. This means that when the future water bottom level is implemented, the same activities can take place. So the solution ultimately chosen, reinforcing or renewing the existing quay, must be able to facilitate this.
- **BAM**: Finally, construction company BAM is also involved in this project as a contractor. Since, as contractors, they are responsible for the safe design of structures, a goal for them is to deliver a design that meets the set requirements and guidelines. However, they also join the common goal of designing as circularly as possible since BAM is also currently working to make their business operations more sustainable. Finally, most contracts within construction projects make contractors responsible for the overall cost of a construction project. For BAM, it is therefore also important to minimise the total costs of the project.

From these stakeholders, three specific goals have been identified: firstly, minimising environmental impact; secondly, minimising costs; and thirdly developing a design that meets set requirements and guidelines. In construction terms, the third goal is simply called a design that satisfies. To minimise the environmental impact and costs, it is preferred to strengthen the considered quay walls by applying structural adjustments rather than completely renewing the quays. Therefore, the ultimate goal is to find the preferred configuration of structural adjustments to extend the lifetime of an existing quay wall by 50 years for minimal costs and environmental impact. Ultimately, this should be the configuration that contains the highest aggregated preference score of the stakeholders mentioned above. A 50-year extension is chosen as it aligns with a common target lifetime when designing new quay walls [8].

1.2. Problem definition

To arrive at a reinforced design of a quay wall, it should first be verified that the design of a quay requires adjustments to withstand the future water bottom level. After this verification, a variant study can be conducted. This process involves many design iteration as the dimensions of each adjustment and the combinations of adjustments should be varied. Both the verification of the need for adjustments and the variant study are usually carried out during the preliminary design phase. At this stage, the available information about a specific case is often limited. The calculations executed for both processes therefore include many uncertainties and use many assumptions for the inputs. However, if more information about the considered case becomes available over time, it may be necessary to revise these calculations. While often computer programs are used for these calculations, executing them is a time-consuming task due to the varying dimensions and combinations of adjustment that have to insert. Additionally, a quay wall always consists of several segments that are designed in a different way due to different conditions. This amplifies the inefficiency issue outlined above, as it applies not just to a single segment but to every segment of the quay wall. As a result, a lot of valuable time and money is wasted that could have been used for other tasks. This is a great waste, as performing these calculations is a repetitive process that could be automated.

Another problem is that the effects in terms of environmental impact and costs are only considered after the variant study already has been completed. As a result, this impact is only known at the end of the preliminary design phase, whereas it could be useful to know it right away. Since these calculation steps are the same for each iteration, this process could be automated as well.

Besides, the current method to determine the preferred configuration of adjustments involves analysing the financial and environmental impacts of various potential variants. Consequently, stakeholders base their preferences on these calculated results, and only then a decision is made regarding which variant to choose. This process is known as an *a-posteriori* decision-making process. This makes it difficult to objectively select the preferred configuration, as every stakeholder wants the configuration that suits their own preference. In order to still collectively choose the preferred configuration, stakeholders often have to compromise on their preferences. However, the preferred configuration of adjustments is found only when a configuration contains the maximum aggregated preference of all stakeholders and satisfies the systems constraints. It is therefore necessary to define the individual preference scores and the systems constraints before the optimisation process. This process is called an *a-priori* design optimisation process which enables to directly determine the preferred configuration of structural adjustments. This configuration then contains the maximum aggregated preference score of all stakeholders while satisfying the systems constraints.

1.3. Relevance of Project

1.3.1. Development Gap

As identified in the problem definition, addressing the inefficiency, lack of insight in financial and environmental impact and the *a-posteriori* determination of the preferred configuration of adjustments, requires an innovative approach. A promising solution is the development of a computational tool that can directly determine the preferred configuration of adjustments for each applicable quay wall. This tool should enable the combination of each stakeholder's objectives to determine a solution that achieves the maximum aggregated preference. This means that the preferred configuration achieved must meet the set design requirements while at the same time it minimises costs and environmental impact. In this way, each stakeholder is involved and customised adjustments can be proposed for each quay wall. While such design optimisation tools have already been developed in the past for the use of newly developed quay walls ([9], [10]), these tools are lacking for existing quay walls. Moreover, the need for upgrading existing quay walls is described by De Gijt [11] in which is stated that the shapes and quay wall structures have remained relatively unchanged during the last 4000 years whereas the size has increased by a factor of ten or more. This is also due to growing ships leading to increased forces on the quay walls. In the paper of Douairi & de Gijt [12], several techniques are suggested to create extra depth in front of (existing) quay walls. These techniques are eventually evaluated in terms of a design that satisfies. However, no optimisation techniques are applied and also no financial or environmental impacts are mentioned. In the paper of El-Naggar [13], a parametric study is conducted showing which parameters show enhancement performance for the steel sheet pile walls. Again, evaluations are performed after the calculations are executed, rather than initially looking for an optimal performance. This problem is described by Grabe & Kinzler [14] who explain that manual searches do not lead to desired target values for geotechnical structures while numerical optimisation can provide methods to support the geotechnical design process. Besides, Ruggeri et al. [15] describe that it is necessary to find solutions to upgrade existing port structures to meet new requirements, instead of developing new ones. In addition, the paper discusses the main issues involved in the geotechnical design for upgrading existing quay walls. Lastly, Geressu et al. [16] proposes a multi-objective optimisation design approach for a diversion weir structure which achieves substantial improvement in stability of the structure and cost. Although the paper developed a method for a weir structure and not for a quay wall, the use of a multi-objective optimisation approach shows a clear added value that can also be applied to the design of a quay wall. Based on the above mentioned literature papers, the development gap that therefore can be addressed is as follows:

> *It is currently impossible to directly determine the configuration of structural adjustments to existing quay walls that contains the maximum aggregated preference of involved stakeholders.*

1.3.2. Development Statement

Based on the development gap and the stakeholders involved who all have a specific objective, the development statement can be formulated as follows:

> *To develop a decision support tool that enables the direct determination of the preferred configuration of structural adjustments to existing quay walls, by applying the Preferendus that maximises the aggregated preference of multiple stakeholders while satisfying technical constraints.*

1.4. Objectives of project

Following the development statement, the aim of this project is to develop a computational tool that is able to directly determine the preferred configuration of structural adjustments for an existing quay wall. Hence, the preferred configuration is found by maximising on the aggregated preference of all stakeholders while satisfying technical constraints. By defining the goals and preference scores of each stakeholder before the optimisation process, this can be implemented. The end user of this tool will be the construction company BAM, who will use the tool during the preliminary design phase in a design process. As mentioned, BAM is currently running into the problem that many calculations have to be made during the preliminary design phase because of the information that becomes available over time. In addition, BAM finds that different segments of quays in a given port or area, can often be reinforced in the same way that were originally conceived differently. Besides, during the preliminary design stage it is currently unclear what the financial and environmental impact is per considered adjustment.

The tool to be developed should therefore automate the process of calculating quay wall designs, assessing their capability to withstand future water bottom levels, testing adjustments and calculating the environmental and financial impact of these adjustments. By automating these tasks, the tool eliminates the need of time-consuming manual calculations. As a result, a lot of time is saved which allows BAM to use this time for specific engineering issues during the preliminary design phase instead of performing basic sums. Additionally, the tool provides immediate insights into the environmental and financial impacts of adjustments, enabling quicker determination of potentially optimal solutions. Furthermore, BAM can more efficiently evaluate whether different quay wall segments can be reinforced similarly. This allows the design of different quay segments to be bundled if they contain the same specific solution. As a result, the implementation process can be optimised by allowing more effective on-site management of materials and equipment, reducing the need for frequent transportation.

1.5. Limitations of project

To develop a computational tool that is able to determine the preferred configuration of structural adjustments, it is necessary to make a number of assumptions. This ensures the tool's generality, making it applicable to any sheet pile wall. The project therefore also contains a number of limitations, which are listed below. These are the main limitations of the entire project. Other minor limitations or assumptions made will be addressed in the relevant chapters of the report:

- **Accuracy of used data**: To identify the preferred configuration, it is necessary to collect financial and sustainability data for each adjustment. However, some of the data collected are based on assumptions, creating uncertainties about the accuracy of the data. For the financial data, for example, only direct construction costs are included. This includes material and machine costs, but personnel costs, for example, are excluded. Moreover, these data were collected in consultation with a cost expert from BAM, who provided costs based on market prices applicable at the time. However, these prices fluctuate over time. For the sustainability data it holds that the data was collected by using DuboCalc, which is a sustainable construction calculator developed by Rijkswaterstaat. Because specific materials or dimensions of adjustments were sometimes missing in this database, some data could not be copied directly. As a result, this data was based as accurately as possible on comparable data that did exist in DuboCalc.

- **Absence of implementation risks**: Implementation risks associated with some considered adjustments are not included in the tool. Therefore, the preferred configuration of adjustments determined by the tool may not be the most preferred configuration to build, as implementing it could involve many risks and uncertainties. Thus, the output of the tool currently gives the theoretically most preferred configuration of adjustments.

- **Absence of measurements**: For the required soil data and corrosion of the considered sheet piles, no actual measurements were carried out, but data included in documentation from the municipalities were used. For corrosion, accurate data can be found by performing own measurements at the considered sheet piles. The same applies to the required soil parameters, which can be found by conducting thorough laboratory tests. If these turn out to be more favourable than the data currently used from the submitted documentation, adjustments may not need to be made at all if the water bottom has to be lowered.

- **Absence of failure mechanisms**: A sheet pile wall contains many failure mechanisms that need to be evaluated before a design is created that satisfies and can actually be implemented. For this project, not every failure mechanism is evaluated, but only the most important and critical failure mechanisms are included in the tool. However, this is in line with the preliminary design phase in which the tool will be used. In this phase, only the most critical failure mechanisms are evaluated.

- **Absence of structural adjustments**: Initially, a list was made of all possible adjustments that could strengthen an existing sheet pile to extend its lifetime. However, due to the scope of the project and because of the integration the tool makes with geotechnical software D-Sheet Piling, not every adjustment was applied. As a result, the adjustments with the most potential and that were best implemented in the tool are included and thus evaluated.

1.6. Thesis Structure

The structure of this thesis is as follows: Chapter 2 explains the theoretical background used in this project. This chapter provides among others an explanation of quay wall structures including its failure mechanisms and the used environmental impact aspects. Consequently, it considers the possible structural adjustments to a sheet pile wall after which the chapter closes by explaining the underlying theory of the Preferendus tool and its optimisation method. Then, chapter 3 describes the project's approach. It explains what the methodology will be, what needs and technical requirements should be included in the tool to be developed, what adjustments will be applied and, finally, how the optimisation process will be set up. Chapter 4 dives deep into the case studies results. The developed tool is applied on three case studies, which all three are in the industrial harbour Loven of Tilburg. This chapter presents the results of the tool and the verification of those results. Then, chapter 5 initially highlights the results from the conducted sensitivity analysis. Subsequently, it reflects on the outcomes of the case studies and the sensitivity analyses. Additionally, that chapter discusses the tool's validation as well. Concluding the thesis, chapter 6 offers an in-depth conclusion and proposes recommendations for future research.

2
Theoretical Background

This chapter sets out the main theories of the project, focusing on four areas. First, it presents general background information of quay walls. This section outlines a brief description of different types of quay walls, followed by an introduction on soil mechanics after which it explains the failure mechanisms and calculation methods of quay walls. Consequently, it describes the environmental impact aspects used during the project. Hereafter, it highlights the different options of strengthening an existing quay wall by zooming in on specific structural adjustments. The chapter concludes with a detailed explanation of the Preferendus and its added value.

2.1. Quay Walls

2.1.1. Classification of Quay Walls

Quay walls are marine structures that are placed between soil and water to ensure safe and efficient handling of ships with their surroundings [5]. Multiple types of quay walls exist, since each type serves different needs. For example, quay walls are used at inland waterways, in city centres, in commercial port areas but also in flood defence systems. Figure 2.1 shows the classification of different quay walls. More types exist, however these are the main ones that are also the most widely used:

1. **Gravity Walls**: Figure 2.1a shows gravity walls. Gravity walls use their weight to counteract earth pressure and are often made of materials like concrete and stone. They are primarily used when the subsoil either possesses adequate bearing capacity or is unsuitable for a sheet pile wall [17].
2. **Sheet Pile Walls**: Figure 2.1b shows sheet pile walls. A sheet pile wall typically consists of vertical elements that are driven deep into the subsoil and may be anchored. The functionality and stability of sheet pile wall structures depend on the soil's ability to keep them in place. They are used when the subsoil has insufficient bearing capacity and is easily penetrable [17].
3. **Structure with Relieving Platform**: Figure 2.1c shows a sheet pile structure with a relieving platform. The configuration comprises three key components. Firstly, there's the sheet pile, which serves as a support and retaining structure between water and land side. Secondly, there's a foundation system consisting of tension and bearing piles on the land side. Lastly, there's a relieving structure that connects the sheet pile to the land-side piles. These structures come into play when there are large retaining heights or when heavy loads are applied to the ground level. [17].
4. **Open Berth Quay**: Figure 2.1d shows an open berth quay. This construction features a horizontal deck above the waterline, supported by both vertical and inclined piles. It's typically used in situations where existing slopes exist or when the subsoil quality is relatively poor [17].

As stated, more types of quay walls exist. This is due the fact that every project has different surrounding conditions on which the quay wall is designed. Moreover, the requirements differ for each case as to which type of quay wall is best to use. For this project, the focus will be on the Sheet Pile Wall type, as this is the type that is widely used throughout the ports of Rhombus UPSIDE and the rest of the Netherlands.

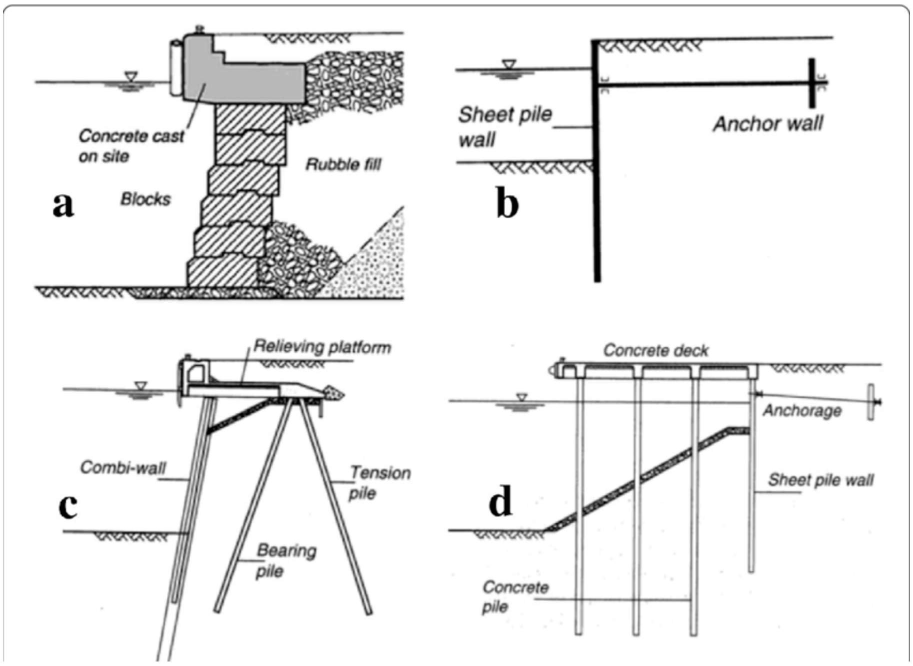


Figure 2.1: Classifications of Quay Walls: a) Gravity wall; b) Sheet pile wall; c) Structure with relieving platform; d) Open berth quay [18]

2.1.2. Soil Mechanics

A sheet pile should be checked against three criteria to assess whether the design of the sheet pile satisfies. These are the stiffness, stability and strength of the sheet pile, which are the main criteria to be met in structural engineering [19]. Therefore, this section briefly explains the soil stresses acting on a sheet pile, as these are the main stresses that act on a sheet pile. This is needed to elaborate on possible adjustments to reinforce the sheet pile in more detail.

Soil consists mainly of water, grains and air [20]. Due to the soil's weight and density, a vertical soil stress exists on a certain level. This stress is caused by the weight of all layers of soil above that level, including water. Soil stress thus consists of the stress of the grains and the pore pressure. According to Terzaghi [20], this leads to equation 2.1:

$$\sigma = \sigma' + p \tag{2.1}$$

in which σ is the total soil stress [kPa], σ' is the stress of the grains [kPa] and p is the pore pressure [kPa]. Following this, the soil stress of a soil layer can be calculated by equation 2.2 [20]:

$$\sigma = h * \gamma_{soil} \tag{2.2}$$

in which h is the height or thickness of a soil layer [m] and γ_{soil} is the volumetric weight [kN/m^3] of a specific soil layer. In case of pore pressure at a soil layer, this can be calculated by equation 2.3 [20]:

$$p = h * \gamma_{water} \tag{2.3}$$

in which γ_{water} is the volumetric weight [kN/m^3] of water, which approximately is equal to 10 kN/m^3 and therefore is set to 10 kN/m^3 for this project. When the soil stress and pore pressure of a soil layer is calculated, the vertical grain stress of a soil layer, also called the effective soil stress, can be calculated by equation 2.4 [20]:

$$\sigma_v' = \sigma - p \tag{2.4}$$

Due to functional requirements, a vertical top load may be active at the ground level of a quay wall. The total soil pressure that is acting on a sheet pile can then be calculated by equation 2.5 [20]:

$$\sigma = (\sum_{i=1}^{n} d_i * \gamma_i) + q \tag{2.5}$$

in which n is the amount of soil layers, i is the considered soil layer, d is the thickness of a layer [m] and q is the load that is active on the top level of all soil layers [kPa]. Figure 2.2 shows a cross section of a sheet pile, in which the geometry, soil pressures and water pressures are included to visualise the above mentioned theory.

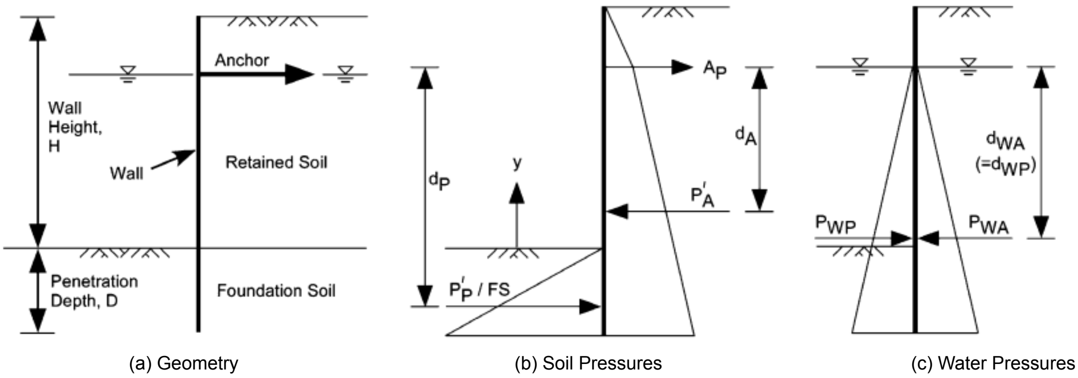


Figure 2.2: Typical sheet pile section showing the geometry, soil pressures and water pressures [21]

As figures 2.2b and 2.2c show, both the soil and water pressure result in a horizontal force acting on the sheet pile. The resulting horizontal force is a side pressure that arises of the vertical effective stress that is calculated by equation 2.4. It occurs on both sides of the sheet pile and as a result, a distinction can be made between the active and passive side of a sheet pile wall, which can be explained as follows:

1. **The Active Side**: The active side of the sheet pile faces the soil it is retaining. In this position, the soil exerts a lateral force known as the active earth pressure, pushing against the sheet pile. Figures 2.2b and 2.2c thus show the active side on the right side of the figures. In those figures, the active soil pressure and active water pressure are shown by P_A' and P_{WA} respectively. The active horizontal pressure can be calculated using equation 2.6 [20]:

$$\sigma_{xx} = K_a * \sigma_v^{'} - 2 * c * \sqrt{K_a} \tag{2.6}$$

   in which $\sigma_v^{'}$ is the vertical effective stress of a soil layer, calculated by equation 2.4 and c is the cohesion of the soil [N/m^2] which refers to its ability to resist shear forces and hold its particles together. According to the theory of Coulomb [20], K_a is the coefficient of horizontal soil pressure which can be calculated using equation 2.7:

$$K_a = \frac{1 - \sin\phi}{1 + \sin\phi} \tag{2.7}$$

   in which ϕ is the angle of internal friction [degrees] of a specific soil layer, which is the measure of ability to withstand shear stress [20].

2. **The Passive Side**: The passive side faces away from the retained soil. Here, the soil provides a counteracting resistance, termed passive earth pressure. This force acts as a stabilizer, preventing further shifting of the pile. Figures 2.2b and 2.2c thus show the passive side on the left side of the figures. In those figures, the passive soil pressure and passive water pressure are shown by P_P' and P_{WP} respectively. The passive horizontal pressure can be calculated using equation 2.8 [20]:

$$\sigma_{xx} = K_p * \sigma_v^{'} + 2 * c * \sqrt{K_p} \tag{2.8}$$

in which K_p is the coefficient of passive soil pressure which, according to the theory of Coulomb [20], can be calculated using equation 2.9:

$$K_p = \frac{1 + \sin\phi}{1 - \sin\phi} \tag{2.9}$$

2.1.3. Failure mechanisms

A sheet pile wall has multiple failure mechanisms. Figure 2.3 shows the fault tree of a sheet pile wall [22]. In this fault tree, all possible failure mechanisms that can lead to the failure of a sheet pile are included. This fault tree is in accordance with the CUR166, which is a handbook that covers all methods that are applicable in the Netherlands for the design, execution and maintenance of sheet pile structures [8].

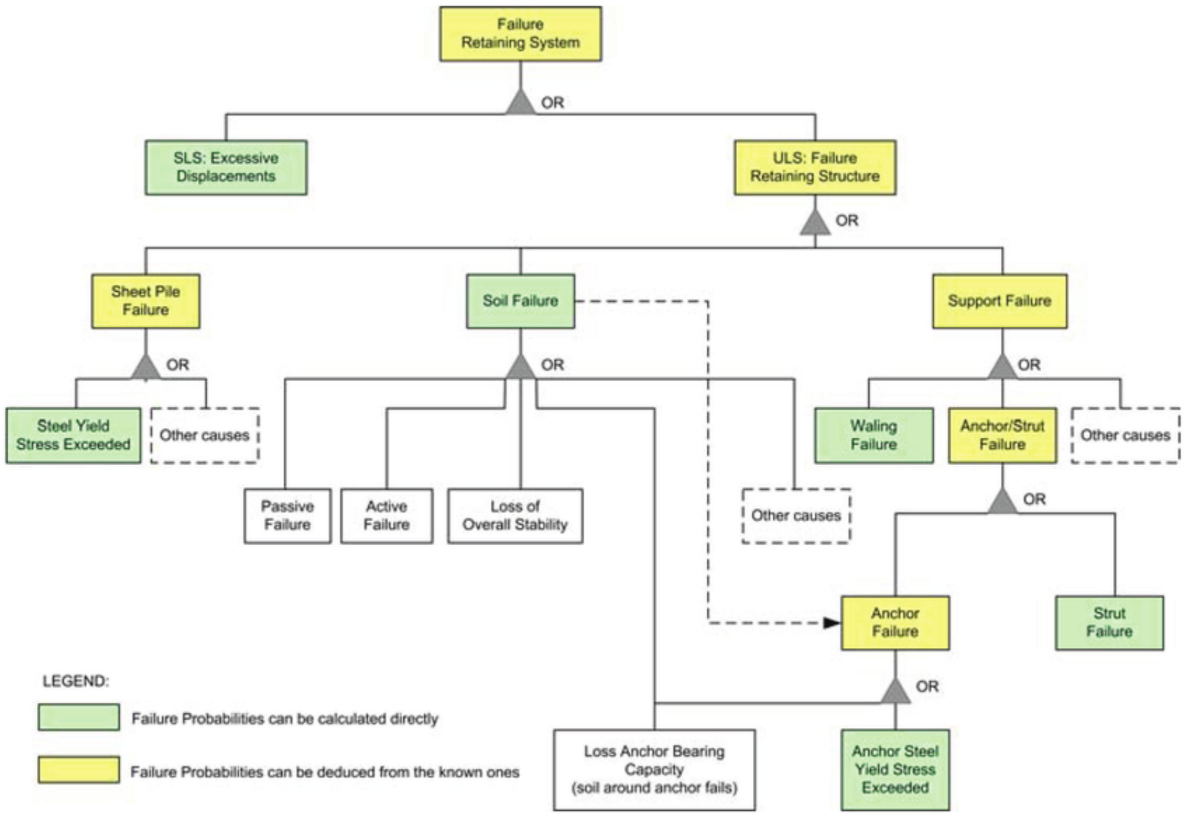


Figure 2.3: Fault Tree of a Sheet Pile Wall [22]

Following this fault tree, the critical failure mechanisms that should be evaluated are listed below. Please note that these are not all existing failure mechanisms. However, as the tool is intended for use in the preliminary design phase, it is sufficient to include only the most critical failure mechanisms. For each of these mechanisms, a unity check can determine whether this failure mechanism is excluded in a sheet pile wall construction. A Unity Check (UC) is calculated to determine whether a sheet pile wall can withstand the forces and moments acting on it without exceeding its design limits. The check can be evaluated for any component of a sheet pile, including an anchor, for example. This check can be calculated by dividing the obtained value that is present in a sheet pile by the maximum theoretical capacity of a sheet pile, which is a material-specific value. When considering the unity check for the bending moment for example, the occurring bending moment M_{sd}, is divided by the material-specific value of the steel used of the sheet pile [8] which is denoted by M_{rd}. If this value is less than 1, the unity check is sufficient for that failure mechanism. In formula form, this is as follows (equation 2.10):

$$UC_M = \frac{M_{sd}}{M_{rd}} \leq 1 \tag{2.10}$$

in which M_{sd} is the obtained or calculated value of the bending moment [kNm/m] and M_{rd} is the material-specific value of the steel used of the sheet pile wall [kNm/m].

In structural engineering, the Ultimate Limit State (ULS) and the Serviceability Limit State (SLS) are two important design considerations used to assess the performance of structures like sheet piles. In general, the Ultimate Limit State (ULS) primarily focuses on the safety and structural integrity of a sheet pile under extreme loading conditions, ensuring it can withstand the worst-case scenarios. In contrast, the Serviceability Limit State (SLS) concentrates on the performance and functionality of the sheet pile under normal service conditions, ensuring it meets user requirements and remains functional. According to the CUR166 [8], it defers which parameters to use for a calculation based on which design consideration one is using. For the SLS, one should use all representative values of all necessary soil parameters and using partial factors that are equal to 1. A partial factor is a factor to which the value of a certain load is multiplied by to calculate the correct calculation value. However, if one is considering the ULS, a partial factor should be used that is bigger than 1, depending on the safety class one is using. In addition, a safety margin should be included as a raise on the geometry parameters. This is again depending on the safety class that is used and also depending on the type of parameter. The CUR166 [8] includes a table in which those partial factors and safety margins are stated. This table also explains how to determine the dimensions of a sheet pile design. These calculations are called sizing calculations and involve several steps. These steps go from step 6.1 to 6.5 plus step 6.5 x factor. Herein, steps 6.1 to 6.4 are ULS calculations, in which the partial factors and safety margins are applied. In step 6.5, the SLS is calculated, and in step 6.5 x factor, the SLS is multiplied by a factor of 1.2 to find the required calculation values for the bending moment, shear force and any anchor force. All these steps need to be completed to check whether the sheet pile design satisfies. This includes that every construction stage when reinforcing a quay wall is assessed with the CUR steps. If a failure mechanism is found to occur in 1 of these steps, the sheet pile design does not satisfy and adjustments must be made to the design.

In short, to correctly calculate the unity check of the occurring bending moment, shear force, anchor force or displacement, a distinguish should be made whether to calculate the value for the ULS or the SLS. Figure 2.3 shows what are the most critical failure mechanisms and if they should be calculated during the ULS or SLS. Each of them is described below:

1. **Total displacement of the Sheet Pile Wall**: The total displacement of a sheet pile wall needs to be calculated in the SLS. This means no safety margings need to be included on the geometry parameters of the sheet pile wall and a partial factor of 1.0 should be used. According to the CUR166 guidelines [8], the unity check of the total displacement involves that the occurring maximal displacement u_{max} should be less or equal than the maximal allowable deformation u_{limit}. The value of u_{limit} should be defined by the client in the programme of requirements. If this value is missing, an own limit must be maintained below which the maximum deflection must remain. Currently, BAM is using a value of $\frac{1}{100} * H_{retaining}$ if u_{max} is missing, in which $H_{retaining}$ is the retaining height of the sheet pile. Following these statements, the unity check of the total displacement UC_D can be calculated using the following equation (2.11):

$$UC_D = \frac{u_{max}}{\frac{1}{100} * H_{retaining}} \leq 1,0 \tag{2.11}$$

   in which u_{max} is the occurring maximal displacement [mm] and $H_{retaining}$ is the retaining height of the sheet pile [m].

2. **Failure of the Sheet Pile**: This failure mechanism occurs when the obtained or calculated yield stress exceeds the maximum allowable stress which is a material-specific value. In typical design guidelines, the main force exerted on sheet piles is believed to be the bending moment resulting from horizontal pressures produced by soil and groundwater [22]. Therefore according to the

CUR166 [8] the unity check for the bending moment capacity can be calculated in the ULS using equation 2.10. Whereas M_{sd} can be calculated depending on the specific soil and geometry parameters of the sheet pile wall, M_{rd} should be calculated using material depending values. This is called the design moment capacity [kNm/m] and is calculated according equation 2.12 [22]:

$$M_{rd} = W_{el} * f_y \tag{2.12}$$

in which W_{el} is the elastic section modulus [m^3/m] and f_y [kPa] is the steel yield strength. Whereas the value of W_{el} is depending on the geometry of the sheet pile wall profile that is used, the value of f_y is depending on the steel grade that is used.

Next to the bending moment capacity, the unity check for the shear force capacity should be calculated as well. The NEN-EN 1993-5:2023, which is the Eurocode 3 which includes guidelines for the design and calculation for steel constructions [23], includes that the design value of shear force V_{sd} should be lower or equal to the design plastic shear resistance V_{rd}. Therefore, the unity check for the shear force capacity UC_V can be calculated following equation 2.13:

$$UC_V = \frac{V_{sd}}{V_{rd}} \leq 1,0 \tag{2.13}$$

in which V_{sd} is the shear force [kN/m] that is calculated depending on the specific soil and geometry parameters of the sheet pile wall and V_{rd} is the plastic shear resistance [kN/m] depending on the geometry of the sheet pile profile and the steel grade that is used. The plastic shear resistance V_{rd} can be calculated by using the following equation 2.14:

$$V_{rd} = \frac{A_v * f_y}{\sqrt{3} * \gamma_{m0}} \tag{2.14}$$

in which A_v is the shear area [m^2] and γ_{m0} is the partial factor that is depending on the safety class that is applied. The shear area A_v is calculated using the following equation 2.15:

$$A_v = t_w * (h - t_f) \tag{2.15}$$

in which t_w is the web thickness [mm], h is the depth of the cross-section [mm] and t_f is the flange thickness [mm].

3. **Failure of the Soil**: This failure mechanism happens when the horizontal forces acting on the sheet pile are not in balance. A sheet pile wall must maintain force equilibrium to among others ensure its stability. Force equilibrium means that the sum of forces acting on the wall in both the horizontal and vertical directions is balanced. To meet this horizontal equilibrium, the passive pressure must in any case be equal or greater than the active pressure to ensure the stability of a sheet pile wall. Since the overall stability of the sheet pile wall should be checked for this failure mechanism, no unity check has to be executed. This is a functionality that can be calculated during the ULS automatically by D-sheet Piling or PLAXIS, which are both programs to calculate a sheet pile wall, which chapter 3 will explain in more detail.

4. **Failure of the Support**: This failure mechanism happens when a supporting structure of a sheet pile wall construction fails. This could be an anchor or a strut, but other types of support exist as well. The anchor can fail due to multiple components, but for this project the failure of the steel body is considered. It is assumed here that the original anchors and their associated components are designed with a similar value for the unity check. Therefore, when the anchor force has increased in a given case and the unity check of the steel body satisfies, it is assumed that the unity check of the other components of the anchor also satisfies. The steel body of an anchor may fail if the resulting or operating anchor force $E_{ULS;d}$ [kN] exceeds the structural resistance $R_{t;d}$ [kN] of the steel used. This results in the following unity check for the anchor capacity UC_A, stated in equation 2.16 and included in the NEN9997-1+C2:2017 [24]:

$$UC_A = \frac{E_{ULS;d}}{R_{t;d}/\gamma_{A;NL}} \leq 1,0 \quad (2.16)$$

in which $\gamma_{A;NL}$ is the conversion factor for anchors in the Netherlands, which is 1.25 according to the EN 1993-5 [23]. And $E_{ULS;d}$ is the operating anchor force, which can be calculated according equation 2.17:

$$E_{ULS;d} = F_{ULS;d} = P_{max} * c.t.c \quad (2.17)$$

in which P_{max} is the anchor force per meter between the anchors [kN/m] and c.t.c is the center-to-center distance between the anchors [m]. The structural resistance $R_{t;d}$ can be calculated according equation 2.18 [24]:

$$R_{td} = F_{tg;Rd} = \frac{f_y * A_{steel}}{\gamma_{M0}} \quad (2.18)$$

in which f_y is the characteristic value of the yield strength of the steel used [N/mm^2], A_{steel} is the cross section of the anchor [mm^2] and γ_{M0} is the material factor regarding the yield strength of the anchor material. For the considered quay walls in this project, construction steel is used as material which corresponds to a factor of 1 for γ_{M0}.

2.1.4. Calculation Methods

Different calculations methods exist to calculate the internal forces of a sheet pile wall that all have an other different underlying theory which it is based on. Below, the different methods are listed and shortly explained:

- **Method of BLUM**: The method of BLUM suggests that the interaction between the sheet pile wall and its surrounding soil can be simplified into a statically defined analytical framework. In this model, only the soil's strength matters, while the soil's deformation characteristics and the rigidity of the sheet pile wall don't affect the results. The model presumes that wall movement causes active and passive soil breakdown on opposite sides of the sheet pile. However, a limitation of this approach is that the calculated displacements might not be very accurate, as it doesn't consider the soil's stiffness [8].

- **Spring supported beam model**: Contrary to the method of BLUM, active and passive pressures arise based on soil movement. Without any soil movement, the soil pressure remains neutral. To represent this, the sheet pile wall is visualised as an elastic beam supported by springs, which may have a changing bending rigidity of the stiffness EI. The soil's movements are considered through horizontal bedding values. Consequently, the horizontal pressure from the soil on the sheet pile is determined by soil movements, which are influenced by the stresses [8]. The spring supported beam model is developed in the computer program D-Sheet Piling (known as Dsheet), which will be used throughout this project and further explained in chapter 3.

- **Finite Element Method (FEM)**: This method involves a digital model designed to compute stresses and deformations within a soil mass and built components within, like sheet piles, anchor rods, and anchor walls. The software PLAXIS serves as a computational model for tackling soil mechanics challenges that aren't solvable through analytical methods. Using this software, one can analyze the stress, deformation, and stability of soil masses with intricate shapes including complex soil-structure interaction. The structure is segmented into distinct parts, and attributes like weight, rigidity, and resilience are allocated to these segments [8].

Currently, the spring supported beam model and FEM are the methods that are widely used in the Netherlands [8]. This is because the BLUM method has certain limitations that prevent correct results from being obtained. By using Dsheet or PLAXIS, which are the computer programs of the spring supported beam model and FEM respectively, the following elements can be considered as better compared to BLUM's method [8]:

1. The deformations of both the surrounding soil and the sheet pile wall it self
2. The pretension forces of anchors that are in place
3. Different construction phases of a sheet pile wall construction project
4. Overconsolidation due to past overburden from, for example, land ice or former embankments.

As BLUM's method has certain limitations, it will only be used to gain an initial understanding of the conditions and outcomes of a sheet pile wall. However, gaining this insight is useful because BLUM's method is relatively easy to apply, whereas using the Dsheet and PLAXIS software can feel like a black box model if you have little geotechnical knowledge or no experience in using this software. When Dsheet is used, the program will calculate both the ULS and SLS automatically using the partial factors and safety margins defined in the CUR166 [8]. In PLAXIS, one should apply the partial factors and safety margins self to create both the SLS and ULS design considerations. Chapter 3 provides a thorough explanation how BLUM, Dsheet and PLAXIS will be used throughout this project.

2.1.5. Corrosion

As years pass by, materials of a sheet pile wall are influenced by surrounding conditions. For steel sheet piles, corrosion is one of the factors to be taken into account as it can lead to thickness loss. The same applies to an anchor, where corrosion can lead to decrease in diameter. The CUR166 [8] includes the total reduction in thickness due to corrosion for a number of environments for a steel sheet pile wall. For this project, a uniform corrosion rate is assumed over the entire sheet pile. However, it should be noted that the corrosion rate can vary greatly over different zones of the sheet piling. In addition, it is possible that the corrosion rate in general may occur more unfavourably or more favourably than stated in CUR166. It is therefore recommended to take measurements at a sheet pile wall in order to arrive at the current thickness rather than uniformly adopting the corrosion velocities from the CUR166. However, because a generic tool is being developed in this project, it was decided to adopt a corrosion rate from CUR166 that applies to the entire sheet pile.

Since a sheet pile wall has one side facing the soil and one side facing the water, corrosion has to be considered on both sides. A target life of 50 years and undisturbed, clean soil is assumed for the deterioration of a sheet pile on the land side. This corresponds to an deterioration of 0.60mm in 50 years [8], which equals a corrosion rate v_l of 0.012mm per year. For the deterioration on the water side, clean, fresh water is assumed with again a lifetime of 50 years. This corresponds to an deterioration of 0.90 mm in 50 years, corresponding to a corrosion rate v_w of 0.018 mm/year [8]. To calculate the current thickness t [mm] of a sheet pile wall, equation 2.19 should be used:

$$t = t_0 - (T_u * v_w + T_u * v_l) \tag{2.19}$$

in which t_0 is the original thickness of the sheet pile profile [mm] and T_u are the amount of years that the sheet pile is being used [years]. Based on t, the percentage in thickness reduction R_t can be calculated according equation 2.20:

$$R_t = \frac{t - t_0}{t_0} * 100\% \tag{2.20}$$

Eventually, the thickness of the wall is also influencing the elastic section modulus W_{el} of the sheet pile profile. The reduction that has taken place on the thickness of the wall, can be assumed the same on the elastic section modulus of the sheet pile. Using equation 2.21 the current elastic section modulus W_{el} can be calculated:

$$W_{el} = W_{el;0} * (1 + R_t) \tag{2.21}$$

in which $W_{el;0}$ is the original elastic section modulus [cm^3/m] of the sheet pile wall, depending on which profile is being used. The corrosion rate that is applicable on the elastic section modulus should also be included in the unity check of the bending moment of the sheet pile, which was calculated according equation 2.10. Here, the obtained bending moment M_{sd} is calculated at T_u, while the capacity M_{rd} is calculated at the design lifetime denoted as T_l. In this way, the design is evaluated in a conservative way, so that a structural engineer can guarantee that the design of a sheet pile satisfies. For this project, a lifetime of 50 years is assumed for the strengthening of the sheet piles, T_l. This means that the sheet pile wall should be strengthened in such a way that it can exist for an additional 50 years, on top of the already covered T_u years. To implement this, the reduction in equation 2.20 should be recalculated. It then applies that the current thickness in equation 2.19 should be the thickness at the end of the lifetime of the sheet pile t_l, where the original thickness becomes the previously calculated t. In formula form, this results in the following equations 2.22, 2.23 and 2.24:

$$t_l = t - (T_l * v_w + T_l * v_l) \tag{2.22}$$

$$R_{t_l} = \frac{t_l - t}{t} * 100\% \tag{2.23}$$

$$W_{el;l} = W_{el} * (1 + R_{t_l}) \tag{2.24}$$

The reduction of the thickness also applies to the moment of inertia I [m^4] in the same way as equations 2.21 and 2.24, which eventually applies to the stiffness of the sheet pile EI as well.

As stated, corrosion is also a factor to take into account for the diameter of an anchor. However, as an anchor is only surrounded by soil and not by water, only the corrosion rate of the land side applies here. This is the same rate as for the sheet pile, namely v_l which was equal to 0.012 mm/year. The current radius of an anchor r can thus be calculated according equation 2.25:

$$r = r_0 - (v_l * T_u) \tag{2.25}$$

in which r_0 is the original radius [mm] of an anchor that is active at a sheet pile wall construction. Using r, the current steel area of an anchor A can be calculated according equation 2.26:

$$A = \pi * r^2 \tag{2.26}$$

Just as the unity check of the bending moment UC_M, the unity check of the anchor capacity UC_A is also affected by corrosion which was calculated according equation 2.16. Again, it holds that the operating anchor force $E_{ULS;d}$ is calculated on T_u and the structural resistance R_{tld} is calculated on T_l. This means that A_{steel} of equation 2.18 is equal to A of equation 2.26. In that formula, it should then hold that the steel area of the anchor is calculated at the end of its lifetime, which is then equal to the amount of years that it is in use T_u plus the extra 50 years T_l. This results in the following updated formulas, stated in equations 2.27 and 2.28:

$$r_l = r - (v_l * T_l) \tag{2.27}$$

$$A_l = \pi * r_l^2 \tag{2.28}$$

2.2. Environmental Impact Aspects

If calculations show that a sheet pile design will not satisfy when the future water bottom is applied, the value retention principle of the MIRT program is followed. This principle holds that the lifespan of existing objects should be extended while making use of existing objects. To extend the lifetime of the sheet pile walls, certain adjustments should be made. To quantify and compare the sustainable impacts of these adjustments, the Environmental Cost Indicator (ECI) can be used. The ECI-price is a single-score indicator expressed in euros. It aggregates all relevant environmental impacts into a single environmental cost score and represents the shadow price of a product or material on the environment [25]. Figure 2.4 shows how a single-score indicator can be calculated by considering various environmental impact categories [26]. For each of those impact categories a certain weight factor is determined by national assessments. By summing up those shadows prices the total environmental costs can be calculated for a certain product or material which is thus known as the ECI-price. As is depicted in the figure, kg CO2-eq is one of the impact categories that is part of the ECI-price. Since kg CO2-eq is more familiar among most people than the ECI-price, it is a common unity to ask for when construction projects are executed. Moreover, the ECI-price is currently mainly used in the Netherlands, while CO2 emissions are mre common globally. Therefore, environmental impact aspects throughout this project will both be expressed in ECI-price as well as the CO2 emissions.

Impact category	Unit	Weighting of results
Climate change – total	kg CO2-eq.	Single-score indicator
Climate change – fossil	kg CO2-eq.	
Climate change – biogenic	kg CO2-eq.	
Climate change – land use and change to land use	kg CO2-eq.	
Ozone layer depletion	kg CFC11-eq.	
Acidification	mol H+-eq.	
Freshwater eutrophication	kg PO4-eq.	
Seawater eutrophication	kg N-eq.	
Land eutrophication	mol N-eq.	
Photochemical ozone formation	kg NMVOC-eq.	
Depletion of abiotic raw materials, minerals, and metals	kg Sb-eq.	
Depletion of abiotic raw materials Fossil fuels	MJ, net cal. val.	
Water use	m3 world eq.	
Fine particulate emissions	Illness incidence	
Ionizing radiation	kBq U235-eq.	
Ecotoxicity (freshwater)	CTUe	
Human toxicity, carcinogenic	CTUh	
Human toxicity, non-carcinogenic	CTUh	
Land-use related impact/soil quality	Dimensionless	

Figure 2.4: Environmental impact categories [26]

To accurately measure the total environmental impact of a product, it is essential to consider its entire life cycle. For this purpose, the life-cycle assessment (LCA) has been developed. A LCA is a systematic approach used to evaluate the environmental aspects and potential impacts associated with a product, service, or process throughout its entire life cycle [27]. This encompasses everything from raw material extraction, through production and use, to final disposal or recycling. Figure 2.5 shows the building assessment module for a LCA, which is in accordance with the eurocode EN15804. In this figure, every stage of a certain material or product is shown. For each stage the ECI can be calculated, to sum up the total ECI price of a certain product. It is also possible to calculate the ECI price during only specific stages, if for example a product is removed at a construction site. It can however be challenging to gather environmental data for a LCA because it comes from many sources, leading to measurements in different categories. This makes direct comparisons difficult. To address this issue, the ECI can be used and simplifies the situation by taking various environmental data points and combining them into one monetary value. This number allows for easier comparisons across different industries.

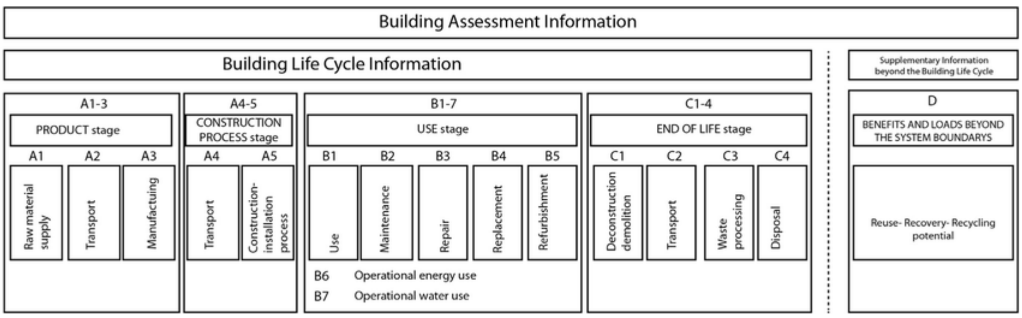


Figure 2.5: Building Assessment Modules for Life Cycle Assesment according to EN15804 [27]

2.3. Structural Adjustments

As section 2.1.2 explained, there is an active and passive earth pressure that works on a sheet pile. Whereas the active earth pressure pushes the wall away from the soil, the passive earth pressure tends to move the wall back to the soil. Therefore, to strengthen a sheet pile and extend its lifetime, one should consider options to lower the active pressure or to increase the passive pressure. In addition, the driving force should be lower than the resisting force of the sheet pile, to ensure sufficient stability and strength [12]. Therefore, another option could be to add stability to the sheet pile to eventually increase the resisting force of the sheet pile. Figure 2.6 shows all possible structural adjustments that can be applied, based on lowering the active pressure, increasing the passive pressure or by adding stability to the sheet pile. These adjustments are as follows:

- Lower the active soil pressure:

  1. **Replacing a soil layer for lightweight material**: All soil layers around the sheet pile are of a specific material with associated soil parameters. One of these soil parameters is the unit weight [kg/m^3]. The higher this unit weight is, the more it contributes to the active soil pressure. One of the measures that can therefore contribute to reducing this active pressure is to change soil layers on the active side for a soil layer of a material with a low unit weight. Examples of such a material are EPS or BIMS.
  2. **Reducing the top load on ground level**: As equation 2.5 included, the top load at ground level contributes to the total active soil pressure. Reducing the top load can therefore be an effective measure in reducing the active pressure. However, the top load is often determined by the functionality behind the sheet pile. This could, for example, be the storage of sand, or the use of a crane to ship goods. Besides reducing the top load, moving it further back could also help. However, due to functional requirements, this would also have to be checked with the user of the quay first.
  3. **Replacing existing soil layers and sheet pile completely for concrete construction**: Another option to reduce the active pressure is to completely replace the existing soil layers and sheet pile with a new concrete structure. In this way, no new sheet pile wall needs to be installed, but a new concrete structure is installed to serve as a quay wall. However, this is a drastic measure that requires many modifications to be implemented.
  4. **Add a drainage**: A drainage serves as a method to remove water from soil, to lower the groundwater level. As equation 2.2 showed, the total soil stress exists of the stress of the grands and the pore pressure. Thus, by adding a drainage, the pore pressure can be lowered which eventually results in a lower total active pressure.
  5. **Lower top level**: By lowering the top level of ground level, soil can be removed which eventually leads to a reduced active pressure according equation 2.5. However, the top level is also determined by functional requirements behind the sheet pile.

- Increase the passive soil pressure:

  6. **Add bacteria to soil layers**: Microbially Induced Calcite Precipitation (MICP) strengthens soil by promoting calcium carbonate formation through bacterial action [28]. This can be applied to soil layers on the passive side of structures such as sheet piles, leading to increased resistance of the passive soil layers. However, this is not common practice yet and should further be explored first.
  7. **Lowering the pile tip level of sheet pile**: By lowering the bottom of the sheet pile and welding on extra material at the top, the sheet pile can be extended. This gives a greater passive wedge to the sheet pile as more soil can be turned over [12]. However, existing anchors must be handled thoroughly as they cannot simply move with the planks being drilled down. It is therefore necessary to start staggering between the planks, by moving the ones without an anchor deeper away and keeping the ones with an anchor attached at the same height.
  8. **Creating a support berm**: By placing an underwater support berm against the sheet pile wall, more resistance is offered leading to an increase in the passive wedge [12]. This

could be of the material grout or underwater concrete, for example. However, it should be investigated whether the retaining berm can be placed so that the top does not rise so far that larger ships cannot pass through the canal.

9. **Placing colloidal concrete**: By placing colloidal concrete, additional support can be provided to the sheet pile wall. This material could be placed as soil layer on the passive side of a sheet pile. Besides providing additional support, it can serve as protection of the underlying soil layers so that the soil is not washed away by ships. A condition for this adjustment is that the top of the underwater concrete floor should not exceed the new excavation level of the harbour.

- Add stability:

10. **Placing anchors above water**: As stated before, stability can be added to the sheet pile wall by placing grout anchors. The tension in the anchor arises from the shear stress between the grout-filled anchor body and the adjacent soil. A steel casing is driven or bored into the ground to a specified depth, and then the anchor rod or strand is placed inside this casing. Subsequently, the gap between the casing and the rod or strand is filled with grout.

11. **Placing underwater anchors**: Currently, the level of most grout anchors being placed is above the waterline. However, research is currently taking place in the Port of Rotterdam, to place grout anchors below the waterline, named underwater anchors [29]. This will allow grout anchors to be used below the waterline. This adjustment has great potential, as the deflections of the sheet pile can be further reduced if the anchor can be placed closer to the bottom of the sheet pile. Since placing an underwater anchor is still an innovative technique, little data is known about it. However, its structural effect can already be studied, making it interesting to demonstrate its added value.

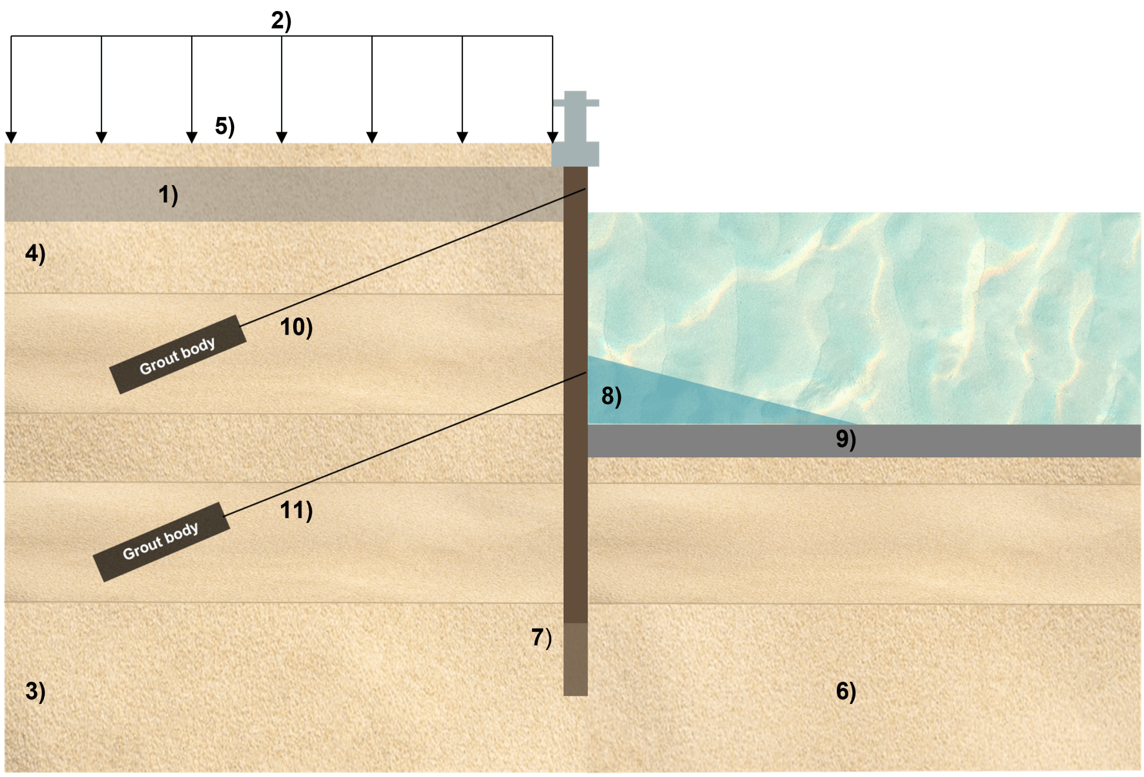


Figure 2.6: Possible structural adjustments sheet pile

2.4. Preferendus

Chapter 1 described that multiple stakeholders are involved in this project. Each of these stakeholders has a different goal to pursue. Because there are multiple goals in this project to ultimately reach an optimal decision, it is a Multi-Objective Design Optimisation (MODO) problem. Multiple methods exist to solve MODO problems. However, for this project a method should be chosen that is able to maximise the preference of each stakeholder while satisfying technical constraints. Therefore, the method that will be used for this project to solve the MODO problem, is the Integrative Maximised Aggregated Preference (IMAP) optimisation method. This method assumes the maximisation of the aggregated preferences of all stakeholders involved [30]. To apply the IMAP method, the decision support tool called the Preferendus will be used, which is an optimisation tool that can be used in the computer program Python. Chapter 3 will explain how the Preferendus is applied within this project. The section below provides a concise explanation of the theoretical foundations of the Preferendus.

Figure 2.7 shows the integration of the Preferendus. The figure shows the interplay between the desirability of involved stakeholders (as shown in the right circle) and the capability of a certain object (as shown in the left circle). In simple words, the Preferendus makes it possible to bring together the desires of a stakeholder, what that stakeholder wants or does not want, with the capabilities of a given object, what that object can or cannot do [30]. The Preferendus can thus be used in problems with multiple stakeholders who have to choose which design variables and quantities are preferred by them. The resulting configuration of design variables can then be assumed as the optimum within the system boundaries for which the aggregated preference score of all stakeholders is maximised. Here, the system boundaries define the limits within the optimisation model, which among others are defined by the bounds of the variables and the constraints. Section 3.4.1 will explain how these are set for this project.

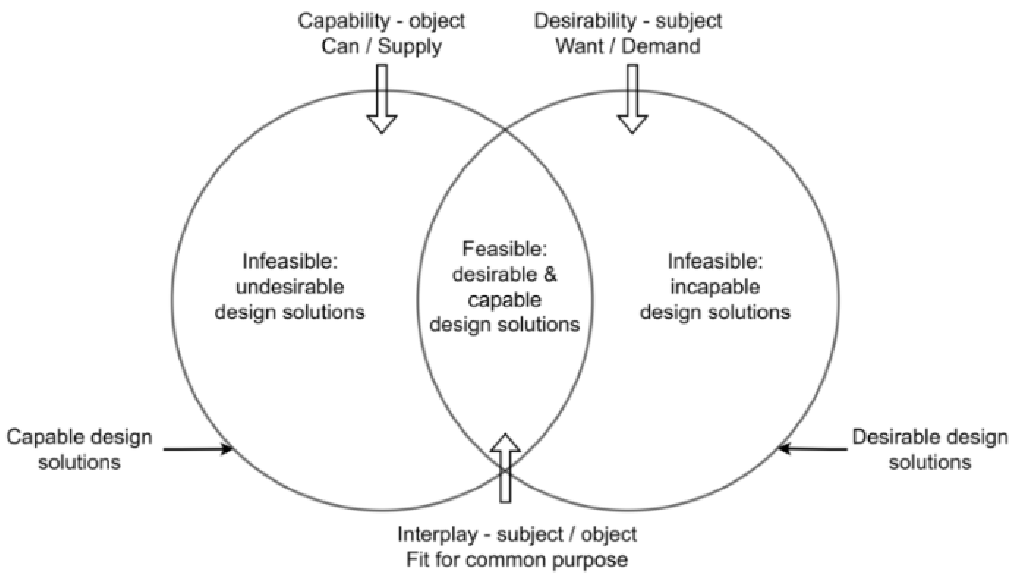


Figure 2.7: The socio-technical interplay between (un)desirability and (in)capability [30]

The Preferendus Tool makes use of a Genetic Algorithm (GA), which tries to find the optimal solution within the set system boundaries [30]. The GA that is being used is specifically developed to make an integration with Tetra. Section 3.1 will explain in more depth the operation of Tetra, but in brief, this is a software which is used to calculate the overall aggregated preference scores of all possible solutions. These scores are ranged from 0-100, where 0 is assigned to the worst design configuration and 100 is assigned to the best design configuration. Thus, if more than two configurations are obtained, the best configuration gets a score of 100, the worst configuration a score of 0, and the other configurations a score in between. These scores are calculated by Tetra, based on the set preference scores of each stakeholder and based on the weights that are given to each stakeholder. By ranging all configurations on this scale, an objective decision can be made by the decision makers which design configuration should be considered as best and thus should be chosen.

Figure 2.8 shows the workflow of the Preferendus. It visualises how a configuration of optimised design variables is found by the Preferendus. Since a GA is used, an initial population of design variables is chosen. From this population, the objectives and resulting total preference score is calculated. From this population, the best design variables are taken to the next population to arrive at a better solution than the previous population. This involves checking whether the conditions of the specific optimisation process, the constraints, are met. This process keeps repeating until the termination criteria are met. This can be, for example, when no change in the final solution has been found for a certain number of generations in a row. The final solution given by the Preferendus is the solution that contains the highest aggregated preference score of all generations and which satisfies the constraints. Since the GA starts with an initial random population from which it further converges to a final result, the user must check whether the provided result can be assumed as the optimal result within the system boundaries. This is because the GA might not have tried all possible solutions. Moreover, it can never be guaranteed that the actual optimal solution is achieved, because a genetic algorithm in itself is not able to guarantee this [30]. As a result, a theoretical chance always exists that the optimal solution has not been found. To check whether the obtained results can be assumed as optimal within the system boundaries, the user can perform several runs of the GA. If multiple runs generate the same answer, the user can assume that the optimal solution has been found. However, for this obtained optimum it still holds true that it is the optimum within the set system boundaries, and one can never guarantee that it is the actual optimum due to the application of a GA. If other boundaries or termination criteria would have been used, another optimal solution could have been found. Should there be differences between the results of multiple runs, it can in any case be concluded that the optimal solution within the system boundaries has not been found by one or more of those runs and adaptations should be made within the model. This includes the settings of the GA it self, which are for example the population size, maximum number of iterations and cross-over function. Chapter 3 will explain these settings in more detail and how they are applied within this project.

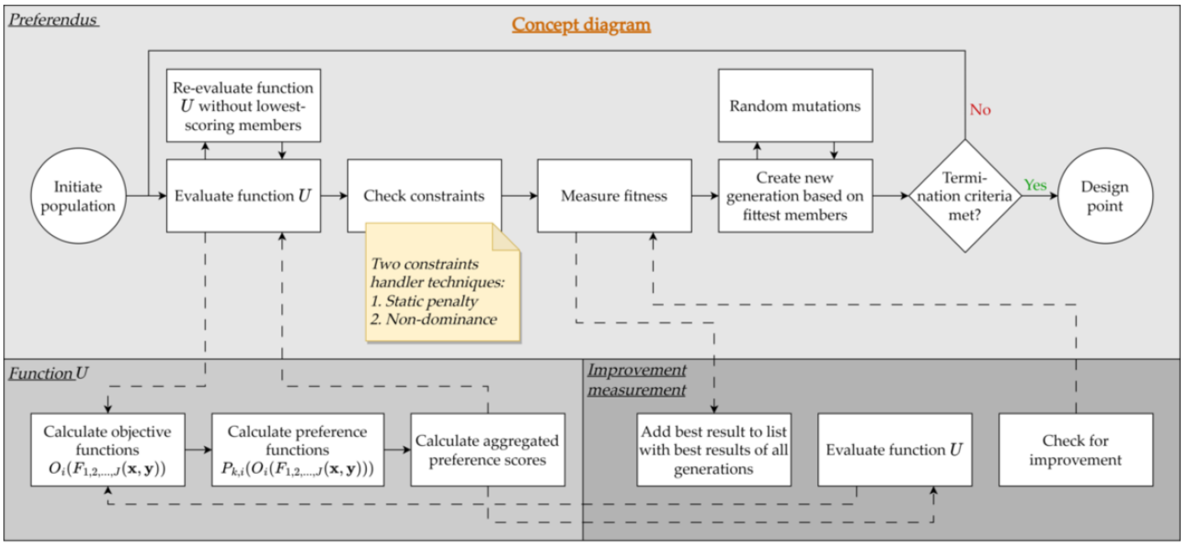


Figure 2.8: The workflow of the Preferendus [30]

3 Approach

This chapter outlines the approach that is used to develop the tool. First, it presents the methodology used, highlighting in particular the programming language and software used. It then elaborates on the needs analysis carried out. This includes all the needs that the tool must be able to meet, including the technical requirements. Following this, the chapter details the applied structural adjustments, selected partly from the list of structural adjustments in the previous chapter. However, not every adjustment of that list is applied in the tool due to several reasons. After this, it explains how the Preferendus is applied in the tool. Hereafter, it elaborates on the implementation steps to create a new sheet pile wall. The last section illustrates a flowchart showing the steps the tool follows during use and the connection between them.

3.1. Methodology

Since the goal of the project is to develop a computational tool, the project is executed by the help of computational science. The tool aims to automate sheet pile calculations, integrate the financial and environmental impact data per adjustment and execute a multi-objective optimisation. To achieve these objectives, it is required to use the capabilities of a programming language and specific software, each chosen for their unique strengths and functionalities. This section highlights the programming language and software used, explaining their role and contribution to the tool's development:

- **Python**: Python is a high-level, general-purpose programming language which has multiple functionalities. It excels in automation tasks, allowing users to efficiently automate repetitive processes [31]. Because it is necessary to determine structural adjustments for multiple sheet piles, which is a repetitive process, Python will be used. This allows the user not to calculate the process manually each time, but to automate it into a script in which these calculations are performed by the computer. Besides, Python will be used to develop a multi-objective optimisation model. To develop this, the 'Preferendus Tool' will be applied which makes use of a GA that is developed in Python.

- **D-Sheet Piling**: D-Sheet Piling is a software which is used to design sheet pile and diaphragm walls and horizontally loaded piles [32]. As stated before, D-Sheet Piling (known as Dsheet), makes use of the spring supported beam model to calculate and design sheet pile walls. It allows an user to design a sheet pile, in which specific soil data, anchor data and/or loads that are active on the sheet pile are included. A benefit of Dsheet is that it takes less calculation time than PLAXIS, which makes use of FEM to be more accurate. Since multiple iterations have to be made which can lead to an increase in computational time, Dsheet will be used as geotechnical program within the decision support tool to calculate the sheet piles and potential adjustments. An already existing application programming interface (API) between Dsheet and Python will be used to control Dsheet from Python. This is needed so that parameters for an existing sheet wall can be entered in Python after which they are automatically sent to Dsheet to calculate the sheet wall. The results from Dsheet are then sent back to Python for an thorough analysis.

- **PLAXIS**: PLAXIS 2D is software that employs the finite element method for geotechnical applications, utilising soil models to simulate soil behavior [33]. Therefore, it can serve as a tool to simulate geotechnical problems, including sheet pile walls. A downside of PLAXIS is the computational time of the program. As it is using FEM, the accuracy of the program is high which however results in the increase in computational time. Due to the many iterations that will be made when testing the adjustments, PLAXIS will not be incorporated in the tool. However, as it is currently known as the most accurate program to calculate sheet piles, it will be used to verify the solutions that come from the tool.
- **Tetra**: Tetra is a software application that implements the Preference Function Modeling (PFM) approach to assess subjective measurements and facilitate multi-criteria decision analysis. It is used to help decision makers in making optimal decisions based on multiple criteria and is based on minimising the least-squares difference between the overall preference score and each of the individual scores by computing its closest counterpart [30]. Simply put, for this project it is used to calculate the overall aggregated preference score of each configuration of structural adjustments.

3.2. Needs-Analysis

Currently, sheet pile calculations are done either through Dsheet or PLAXIS. The data of a sheet pile wall and surrounding soil layers are entered manually, after which the results are calculated. Following this, the results are also analysed manually by usually entering them into an excel spreadsheet, in which the unity checks of considered failure mechanisms are calculated. When the unity checks are above 1, adjustments will be made to the Dsheet or PLAXIS model. Again, this is done in a manual manner after which the results are analysed again until a design is created that satisfies. This iterative design process involves many operations which therefore requires a lot of time. This is a waste, as this design process is identical for each sheet pile and depends only on the input parameters. Moreover, the above only applies to the technical sums of a sheet pile. Here, no information or data has yet been included or calculated on cost, ECI-price and CO2 emissions. This creates the need to develop a tool that automates the above process, making manual calculations unnecessary. In addition, it should provide insight into the financial and environmental impact of certain adjustments. Based on these impacts, the preferred configuration of structural adjustments should then be determined. This would be the one with the highest aggregated preference score of all stakeholders while satisfying the technical constraints, requiring an *a-priori* design optimisation method. Based on these needs, some of the technical requirements to be met by the tool are as follows:

- **Automated tool, dependent only on input data**: This means that only the input data has to be inserted, after which the tool will automatically execute calculations on its own. This input data should consist of sheet pile specifics, geometric specifications, active top loads, use of anchor and if so, the anchor specifics and lastly the soil profiles, including soil materials and corresponding parameters. Also, if turns out that the sheet pile design does not satisfy, adjustments will be tested automatically and the preferred configuration will be the output.
- **Applicable on each existing steel sheet pile**: This requirement arises from the need to efficiently calculate different segments of the considered quay walls. For example, the industrial harbour of Tilburg has approximately 3.8 kilometres of quay wall and has 32 segments that differ of each other. By using the tool, it should take less time to calculate all segments. Besides, it should be applicable on a steel sheet pile as this is the type that is widely used throughout the ports of Rhombus UPSIDE and the rest of the Netherlands. Moreover, the outcome of the tool should also lead to the possible bundling of the different solutions of each segment. This will allow the same adjustments to be applied more efficiently.
- **Tested for failure mechanisms, both without and with adjustments**: As mentioned, the results obtained are currently analysed manually by entering them into an existing spreadsheet. However, it is possible to analyse the obtained results automatically in python. This means that the tool should indicate whether failure mechanisms are active or not. The unity checks that section 2.1.3 described should therefore be included in the tool.
- ***A-priori* design optimisation of structural adjustments**: To be able to directly determine the configuration of structural adjustments that contains the highest aggregated preference score of

all stakeholders while satisfying the technical constraints, it is required to use an *a-priori* design optimisation method. To enable this, the cost, ECI-price and CO2 emissions of each adjustment should also be included. In this way, the financial and environmental impact of the considered adjustments are also determined automatically instead of having to be calculated manually. Using such method should also eliminate the current use of determining this preference *a-posteriori*. As section 2.4 already explained, this can be implemented by applying the optimisation method of Preferendus.

3.3. Considered Adjustments

Section 2.3 described all possible structural adjustments to strengthen a sheet pile wall. However, not each of them is considered to be a potentially applicable adjustment. Besides, not every listed adjustment is equally applicable in Dsheet. Therefore, a choice has been made which structural adjustments are included in the tool, which figure 3.1 shows. To save computational time and find the configuration of adjustments that has the most potential, each considered adjustment that figure 3.1 shows is first tested individually. If an adjustment is found to be applicable, it is taken into the optimisation process. However, if it turns out that the design of a sheet pile does not satisfy when an adjustment has been applied, the adjustment will no longer be considered as a possible adjustment in finding the preferred configuration. In theory, there is a chance that an adjustment that is non-individually applicable could lead to a design that satisfies in combination with another adjustment. Still it is decided to exclude those from the optimisation process, as these apparently have too little impact on the sheet pile design. This could for example be due to the active failure mechanism of the sheet pile, which could require specific adjustments to solve that failure mechanism. Therefore, combining a non-individually applicable adjustment with another adjustment would require a significant amount of this combination to arrive at a design that satisfies. This would lead to an increase in ECI-price, CO2 emissions and total costs compared to the other configurations and it therefore is justified to exclude a non-individually applicable adjustment from the optimisation process.

Each of the considered adjustments is depending on different dimensions, that can be varied to find the theoretical optimum. It is therefore possible that a particular adjustment can only result in a satisfactory design by taking on certain dimensions. As this is different for each adjustment, the varying dimensions per adjustment will be explained below. In order to make as few adjustments to an existing sheet pile as possible, the minimum amount per adjustment is sought to design a sheet pile that satisfies. For clarification, figure 3.1 shows the considered geometry of the sheet pile and the varying dimensions of each adjustment. The list below includes the same numbers for each adjustment as figure 3.1 shows:

1. **Replacing a soil layer for lightweight material**: For this adjustment, it is important to know how thick the lightweight material soil layer becomes. The lightweight material that will be used is BIMS, which is a raw material of lightweight construction elements. It is not desirable for this soil layer to become the top layer on the active side because lightweight materials are often porous materials that may negatively affect the functional requirements of the quay wall. Therefore, it is set that the top level of BIMS starts 1 m below the top level of the top soil layer. From that point, the bottom level of the BIMS layer can be varied. Because pouring BIMS can be done per 0.5 m and because it is also not desirable to dig away more than 2 m of soil, the bottom level will be varied between a minimum of 0.5 m below the top level of the BIMS layer and a maximum of 2 m below top level, with step size 0.5 m. Therefore, the bottom level of BIMS is varied as follows:

$$x_1 \in [T_{sp} - 1.5, T_{sp} - 3] \quad \text{with} \quad \Delta x_1 = -0.5\,\text{m}$$

   in which T_{sp} is the top level [m] of the sheet pile which is equal to the top level of the top soil layer.

7. **Lowering the pile tip level of a sheet pile**: For this adjustment, it is required to know what the new pile tip level will be of the sheet pile. As stated before, it will be necessary to stagger the sheet piles because of the existing anchors. Because of the staggering, the sheet piles are not equally long over the total length of the quay wall. To implement this consequence in the model, the stiffness EI of the additional material will be halved. As a result, the model assumes that the sheet pile is the same length over the entire length of the quay, however, the halved stiffness of the additional material rectifies this effect. As it is not possible to drive the existing sheet piling

deeper than 2 metres, a minimum depth of 0.5 metres and a maximum depth of 2 metres, in 0.5-metre increments, will also apply for this adjustment. The new bottom level of the sheet pile will be varied as follows:

$$x_2 \in [B_{sp} - 0.5, B_{sp} - 2] \quad \text{with} \quad \Delta x_2 = -0.5\,\text{m}$$

in which B_{sp} is the bottom level [m] of the existing sheet pile.

9. **Placing colloidal concrete**: For this adjustment, it is again important to know the thickness of the added colloidal concrete soil layer. The material that will be used is colloidal concrete. The thickness of this concrete layer should not exceed the minimum bottom level of the harbour. Therefore, the top level of the colloidal concrete layer is equal to the minimum bottom level of the necessary excavation. The bottom level of the new layer will vary between 0.5 metres and 2 metres below top level, in increments of 0.5 metres, which results in the following variation:

$$x_3 \in [E_L - 0.5, E_L - 2] \quad \text{with} \quad \Delta x_3 = -0.5\,\text{m}$$

in which E_L is the future excavation level [m] of the harbour.

10. **Placing anchors above water**: For this adjustment can be chosen to vary in length, point of engagement or angle position. As the anchor is above the waterline, the choice was made to fix the point of engagement at 0.5 metres above the waterline. In addition, it was chosen to fix the angle of the anchor with the horizontal at 30 degrees. Common sizes for a grout anchor are angle positions between 30 and 45 degrees, because the grout body has to emerge in a deep sand layer to transfer the forces of the sheet pile into the soil through the friction between the grout body and sand. It holds that, the greater the angle, the greater the vertical force component becomes on the sheet pile. Therefore, an angle of 30 degrees is chosen and there will be varied in anchor length. Here, the minimum anchor length is determined by formula 3.1, where the grout body is 1 metre below the top of the said sand layer:

$$L_{anchor} = \frac{1}{\sin(\alpha)} + \frac{W_L + 0.5 - T_{sand}}{\sin(\alpha)} + 3 \tag{3.1}$$

in which W_L is the water level of the harbour [m], α is the angle between the horizontal and the anchor which is in this case equal to 30 degrees and T_{sand} is the top level of the sand layer the grout body [m] has to emerge. A factor +3 is added to the formula because in Dsheet, the length of the anchor is stopped at the centre of the grout body. Often a grout body is around 6 metres long, half of which is already included in Dsheet and the other half has to be added manually by adding 3 metres to the anchor length. The anchor length will vary in steps of 0.5 m until a maximum of the minimum anchor length plus 1.5 metres, which results in the following variation:

$$x_4 \in [L_{anchor}, L_{anchor} + 1.5] \quad \text{with} \quad \Delta x_4 = 0.5\,\text{m}$$

11. **Placing underwater anchors**: For this adjustment, the anchor's point of engagement below the waterline will be varied. Because there is still little known about the underwater anchor, it is interesting to investigate whether differences in results exist for different points of engagement. Once again, the angle will be set at 30 degrees. However, this time, the length will vary in conjunction with the point of engagement. Therefore the term $W_L + 0.5$ of equation 3.1 becomes the varying point of engagement x_5 so that the minimal length of an underwater anchor can be calculated using the following formula (3.2):

$$L_{UW_{anchor}} = \frac{1}{\sin(\alpha)} + \frac{x_5 - T_{sand}}{\sin(\alpha)} + 3 \tag{3.2}$$

in which x_5 is thus the varying point of engagement [m] for an UW anchor on the sheet pile. Since this point must be below the waterline but still be at such height that the anchor can be placed, it will be varied between a minimum engagement point of 1m below the waterline and a maximum of 1m above the minimum bottom level in increments of 1m in size:

$$x_5 \in [W_L - 1, E_L + 1] \quad \text{with} \quad \Delta x_5 = -1\,\text{m}$$

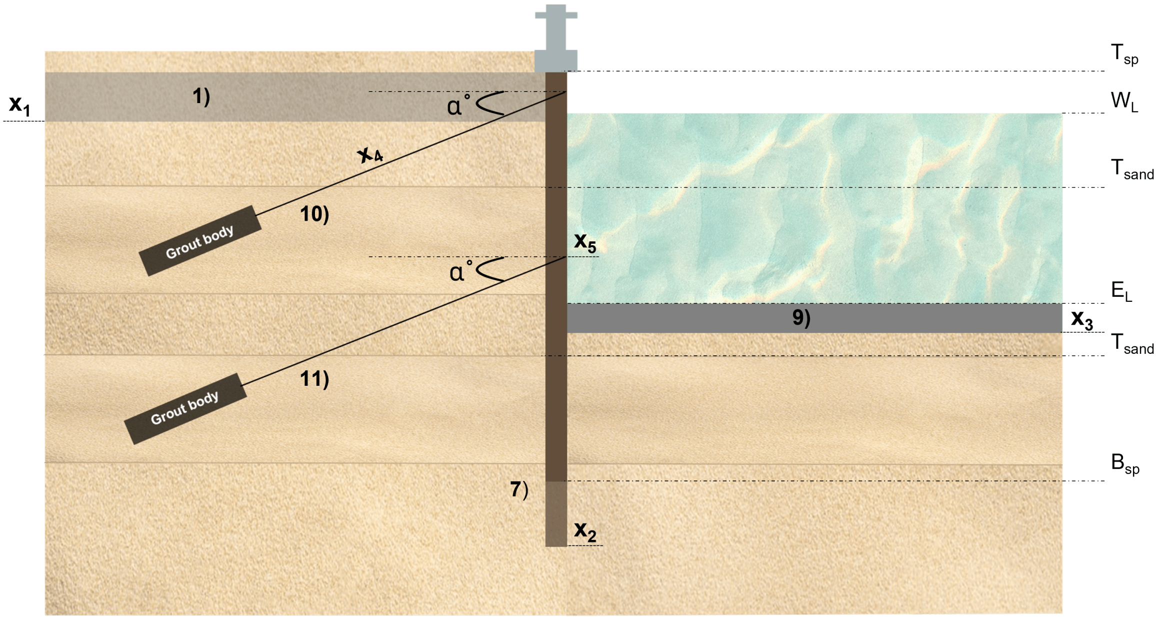


Figure 3.1: Structural adjustments that are applied in the tool

3.4. Optimisation approach

This section first explains how the Preferendus is applied within this project by elaborating on the different levels that section 2.4 described. Hereafter, it discusses the settings of the GA in more detail.

3.4.1. Set-up of Preferendus

As figure 2.7 shows, the preferendus tool exists of three 'levels', which are the capabilities of an object (level 3), the preferences of stakeholders (level 1) and the interplay between those (level 2). This section covers how each level is applied to this project:

- **Level 3: capabilities of objects**: In this level, the variables of the MODO problem are included. As overview, table 3.1 shows each variable and its corresponding bounds which are explained below. The table includes the same variables as figure 3.1 showed. In general, variables that can be added to the model could be of the type *integer*, *real* or *boolean*. Whereas *integers* are numbers without decimals, *reals* have decimals and *boolean* variables can be either true or false. For all variables that are included in the optimisation model, certain *bounds* can be inserted. These bounds define the range within which a variable is allowed to vary or be optimised. The bounds are denoted as follows: $x \in [lb, ub]$, in which lb is the lower bound of a variable and ub is the upper bound.

  For this project, the five structural adjustments that figure 3.1 shows are added to the model as *real* variables. As explained, each of them will be tested individually before it is added to the optimisation model. If turns out that a certain adjustment was not able to create a design that satisfies, that adjustment will not be included as variable in this level. Besides the advantage of reducing computational time, it is also possible to determine the bounds for each variable like this. For each adjustment, the minimum amount that can create a design that satisfies will be sought, which is denoted as min_{x_i} in which i is depending on the type of structural adjustment. Since it is unnecessary to apply more than that required minimum amount, this amount constitutes a bound for each variable. This ensures that in case only one adjustment is chosen as the preferred configuration, no more than this individually required minimum amount min_{x_i} is applied to the sheet pile wall. It differs per variable if this is the upper or lower bound as this depends on the geometry of a specific type of adjustment. Because a combination of adjustments may cause less than this amount to be needed, the other bound of each adjustment must be able to allow this. An option could therefore be to use the bounds that section 3.3 explained. However, then there is a possibility that the lower and upper bound may become equal if the individually required minimum amount min_{x_i} already matches the first varied dimension of an individual adjustment. For example, the required minimum amount of adding BIMS could be $T_{sp} - 1.5$, which is the first varied dimension for that adjustment. As a result, min_{x_i} would be equal to $T_{sp} - 1.5$, which would prevent the amount from being possibly varied for a combination of adjustments if the bounds in the optimisation process would be $T_{sp} - 1.5$ and min_{x_i}. To therefore still be able to seek for the combination of adjustments in which less is used per variable than the individually required minimum amount, slack is given to each variable. This slack involves setting a value lower than this individually required minimum amount for the other bound. Below, the section presents a description of each variable and its associated bounds per adjustment. It uses the same numbers of figure 3.1 for each adjustment in this list:

1. **Replacing a soil layer for BIMS**: For this adjustment the lower bound is equal to min_{x1} and the upper bound is equal to $min_{x1} + 0.5$. So that the bottom level of the BIMS layer is attempted up to a 0.5 metres above the minimum level when it is used in combination with other adjustments. Although it seems that more is added then, less is added because x_1 is the bottom level of BIMS relative to N.A.P. So if min_{x1} is equal to 10.0 +m N.A.P, there will be a less thick layer when this becomes 10.50 +m N.A.P. Keeping it at 0.5 metres ensures that the varying soil level does not exceed the top level of the BIMS layer in any case.
7. **Lowering the pile tip level of a sheet pile**: For this adjustment, the lower bound is equal to min_{x2} and the upper bound is equal to $min_{x2} + 0.5$. Only 0.5 m is given as slack for the upper bound because otherwise there is a chance that the new tip level could rise above the old level.
9. **Placing a colloidal concrete layer**: For this adjustment, the lower bound is equal to min_{x3} and the upper bound is equal to $min_{x3} + 0.5$. Again, only 0.5 m is given as slack since the opportunity holds that it would rise above the future excavation level E_L.
10. **Placing anchors above water**: For this adjustment, the lower bound is equal to $min_{x4} - 2$ and the upper bound is equal to min_{x4}. As the anchor length is varied by $x4$, an attempt is made to find a smaller length that, by combining with other adjustments, can still provide a satisfactory design of the sheet pile. This is enabled by providing a slack of 2.0 metres.
11. **Placing underwater anchors**: For this adjustment, the lower bound is equal to $min_{x5} - 0.5$ and the upper bound is equal to min_{x5}. Here, the point of engagement is varied by $x5$, from which a new anchor length is calculated. Again, by lowering the point of engagement by an additional 0.5 metres, an attempt is made to find a smaller length for the underwater anchor than when it was tested individually.

Next to the structural adjustments that are added as real variables to the model, also *binary* variables are added to the model. Binary variables are represented as *boolean* variables, as only two values can be adopted. For this project, these are 0 or 1, meaning that a certain adjustment is applied to the model in case the variable is equal to 1, or in case that the variable is equal to 0, an adjustment is excluded of the model. This way, the model seeks not only the optimised dimensions but also the preferred types of adjustments. It could be that this is a combination of adjustments, but it could also hold that only one of the adjustments should be applied. Table 3.1 denotes it as x_{ii} where ii is adapted to the amount of working structural adjustments to the sheet pile. This means that in case 3 adjustments are working, 3 binary variables are added to the model, one for each adjustment. Table 3.1 includes all variables for this model as overview.

Variable	Description	Bounds
x_1	Bottom level of BIMS layer	$x_1 \in \{min_{x1}, min_{x1} + 0.5\}$
x_2	Pile tip level of sheet pile	$x_2 \in \{min_{x2}, min_{x2} + 0.5\}$
x_3	Bottom level of colloidal concrete layer	$x_3 \in \{min_{x3}, min_{x3} + 0.5\}$
x_4	Length of anchor above water	$x_4 \in \{min_{x4} - 2, min_{x4}\}$
x_5	Point of engagement of underwater anchor	$x_5 \in \{min_{x5} - 0.5, min_{x5}\}$
x_{ii}	Binary variable	$x_{ii} \in \{0, 1\}$

Table 3.1: Variables and bounds of optimisation model

- **Level 1: preferences of stakeholders**: In this level the preferences of the stakeholders are set. This involves assigning preference scores to values of each objective that belong to a specific stakeholder. Based on these preference values, the preference score of each individual objective can be calculated first on which the aggregated preference score of design configurations can be determined eventually. For this project, four stakeholders are involved, which are the municipalities of the different considered ports, the European Union, a quay wall owner and BAM. As mentioned, their targets are minimising the ECI-price, CO2 emissions and total costs, while a sheet pile design should be created that satisfies. Since it was not possible to talk to all stakeholders and therefore the preference scores could not be based on those conversations, the preference scores are set using the values associated with the objectives when constructing a new sheet pile, as this is the alternative to reinforcing an existing sheet pile wall. Those preference scores can be used to create preference curves in which preference scores (0-100) are put on the y-axis and objective values on the x-axis (user-set values).

  For the ECI-price and CO2 emissions a linear preference curve can be set, as this is in line with the MEAT approach currently applied in infrastructure construction projects. This stands for Most Economically Advantageous Tender (MEAT), an approach where tenders are evaluated based on the concept of achieving the highest value at the most affordable cost [34]. In a tender process, the client then defines how certain discount can be achieved on the total cost when a good score is achieved on, for example, environmental impact aspects, often on a linear basis. A linear preference curve can therefore be drawn up by stating that if 1% of the ECI-price of the new sheet pile situation is obtained as the ECI-price for the reinforced situation, and 1% of the CO2 emissions of the new sheet pile situation is obtained as CO2 emissions for the reinforced situation, a preference score of 100 is obtained for both. On the other hand, a preference score of 0 is obtained if the full 100% of the total ECI-price and CO2 emissions related to the new construction situation is obtained. To construct a linear function, the preferred score of 50 is added for both targets. This score is achieved when 50.5% of the new construction ECI-price or CO2 emissions are achieved to be exactly between 1% and 100%.

  For the total costs however, a negative exponential function is created to show that the preference score decreases quickly when costs increase. Still, a preference score of 0 is again obtained when the total costs of the reinforcing situation are equal to the total costs of the new construction situation. In addition, a preference score 0f 100 is obtained when the total costs of the reinforcing situation are equal to 1% of the total costs of the new construction situation. However, to create the negative exponential function, a preference score of 80 is added to the model. This score is obtained when 10% of the total costs of the new construction situation is obtained as costs for the reinforcing situation. These values are based on expectations of how much the reinforcement situation would cost compared to the new construction situation. It should be noted that these are direct implementation costs. If design costs and risks were included, different total costs might arise that would make this preference score different. The preferred values for both the ECI-price, CO2 emissions and costs are therefore also set so that they can be easily changed by the user of the tool. Table 3.2 shows an overview of the preference scores and corresponding objective values. The specific values of the new sheet pile construction for ECI-price, CO2 emissions and total costs are different for each case considered. Chapter 4 will discuss these.

Objective	Preference score	Corresponding objective values
ECI-price	100:	1% of ECI-price new sheet pile construction
	50:	50.5% of ECI-price of new sheet pile construction
	0:	100% of ECI-price of new sheet pile construction
CO2 emissions	100:	1% of CO2 emissions of new sheet pile construction
	50:	50.5% of CO2 emissions of new sheet pile construction
	0:	100% of CO2 emissions of new sheet pile construction
Costs	100:	1% of total costs of new sheet pile construction
	80:	10% of total costs of new sheet pile construction
	0:	100% of total costs of new sheet pile construction

Table 3.2: Preference settings

Besides the preference scores of each objective, the *weights* of each stakeholder are determined in level 1 as well. These can basically be interpreted as the priority that is assigned to each stakeholder. This is because, during a construction project, the importance of each stakeholder's interests may differ. Therefore, for each objective a different weight w is set. In any case, the sum of all weights should be equal to 1. Table 3.3 shows an overview for the set weights of this project. This shows that the ECI-price and CO2 emissions have a weight of 0.4, as these targets have a higher priority than costs. This is in accordance with the overall goal of the project: making existing sheet pile structures future-proof in a circular and sustainable way. Therefore, a weight of 0.2 is set for the overall costs. Just as the preference scores and corresponding objective values, these weights can be changed easily by the user if other priorities should be assigned to involved stakeholders.

Stakeholder objectve	**Weights**
ECI-price	0.4
CO2 emissions	0.4
Costs	0.2

Table 3.3: Weights of stakeholders

- **Level 2: interplay**: Level 2 incorporates the interplay between the objects' capabilities and stakeholders' preferences. Specifically, it incorporates the *objective functions* and *constraints*. To implement these, it is required to collect data per variable on the different objectives which in this case is data per structural adjustment on the ECI-price, CO2 emissions and costs. This section first present an overview of these data, followed by a description of the objective functions and constraints.

  – **Data**: Tables 3.4 and 3.5 show the sustainable and financial data per structural adjustment. Overall, the user should be aware that there is a certain uncertainty in these data. Because a generic tool is being developed for this project, the tool assumes generic values per considered adjustment, rather than being able to determine project-specifically what the ECI-price, CO2 emissions or total cost would be of each adjustment. Because of this uncertainty, it is important for a potential user of the tool to first evaluate this data each time the tool is used. This is because the data used may have changed over time, or specific quay wall conditions may require adjusting this data. However, since the tool will be be used during the preliminary design phase of a design process, it is justified to use data that has some uncertainty. That is because the ultimate goal is to show which structural adjustments have the most potential to be further investigated for use in a final design. Ultimately during final design, when there are fewer uncertainties and more specific project information has become available, the final ECI-price, CO2 emissions and costs can be determined.

    Special attention should be given to the underwater anchor as well. As mentioned, this is an innovation technique for which this project mainly investigates the technical potential. However, it is not yet a technique that is currently been used on the market already. As a result, little data is known. Therefore, an estimation is made for the required data, which is based on the found data for a grout anchor above the waterline. It is expected that approximately the same values for the ECI-price and CO2 emissions can be used. This is since the same anchor is applied as the anchor that is placed above the waterline, meaning that the same LCA can be assessed. The only difference is that a special machine is developed to apply the underwater anchor, compared to the above-water anchor. However, the development of this machine falls outside the LCA of the underwater anchor, only its use should be included in calculating the ECI-price and CO2 emissions. Since this can be compared to the installation of a grout anchor above the waterline, it can be assumed that these values are similar. For costs, however, it is a different case. Because the application process takes place below the waterline, there are many uncertainties that make estimating costs much more difficult. For example, divers have to work to fix the anchor correctly, and also the condition of the sheet pile itself under water can be very different from the condition above water. Because of these uncertainties, costs can differ by a factor of 2 to 5 compared to above-water anchors. For now, therefore, a factor of 2 is set against the costs of an above-water anchor, as this provides insight into whether the underwater anchor can be a more preferred adjustment than the other considered adjustments. If it turns out that a preferred result has been found in only applying underwater anchors where a factor of 2 has been assumed for the costs, it can be investigated what the maximum costs would be to no longer be considered as preferred result.

Table 3.4 below, shows the ECI-price and CO2 emissions per adjustment. This data is collected by using DuboCalc, which is a sustainable construction calculator developed by Rijkswaterstaat. It can be used to calculate and compare the sustainability and environmental costs of specific products or materials [35]. It calculates the ECI-price and CO2 emissions during the entire life cycle of a certain material or product, as figure 2.5 showed. However, it should be noted that not all materials or processes involved in the reinforcement process may specifically be included in DuboCalc. For example, it is common that not every specific sheet pile profile, such as an AZ-13 or AZ-18, is listed in DuboCalc. Nevertheless, values could be obtained for each adjustment on which accurate estimations could be made. Again it holds that the aim of the tool is providing insight in the differences between adjustments, and to a lesser extent to get the values as correct as possible. A few adjustments have side activities that need to be included in the calculations for the ECI-price and CO2 emissions. The table therefore includes a total ECI-price and CO2 emissions line for each adjustment for clarity. As this total depends on several materials and associated volume units, some materials concerned are indicated in abbreviations. For example, the material of a sheet pile is denoted as 's.p.'. For the adjustment adding BIMS, removing existing soil layers is required as a side activity. As this is releasing material, it should be subtracted from the values of BIMS for the total ECI-price and CO2 emissions. The same applies to the adjustment where colloidal concrete is placed on the passive side. For the adjustment 'extending sheet pile', two components should be considered as well. These are the sheet pile material that is added to extend the sheet pile and, secondly, the cover beam on top of the sheet pile. The cover beam must first be removed before the sheet pile wall can be driven down. A new cover beam must then be installed. For the installation of grout anchors, all the necessary steps to construct those are already included in the values obtained.

Structural adjustment	ECI-price	CO2 emissions
Adding BIMS	Placing BIMS: 9.03 €/m³ Removing soil: -1 €/m³ **Total**: 8 €/m³ BIMS	Placing BIMS: 53.23 kg/m³ Removing soil: -2 kg/m³ **Total**: 51 kg/m³ BIMS
Extending Sheet Pile	Sheet pile (s.p.) material: 41.71 €/m² Removing capping beam (c.b.): 0.16 €/m Placing capping beam: 0.84 €/m **Total**: 42 €/m² s.p. + 1 €/m c.b.	Sheet pile (s.p.) material: 321.3 kg/m² Removing capping beam (c.b.): 1.08 kg/m Placing capping beam: 11.44 kg/m **Total**: 321 kg/m² s.p. + 12.50 kg/m c.b.
Placing colloidal concrete	Colloidal concrete: 18.4 €/m³ Removing soil: -1 €/m³ **Total**: 17 €/m³ colloidal concrete	Colloidal concrete: 183 kg/m³ Removing soil: -2 kg/m³ **Total**: 181 kg/m³ colloidal concrete
Anchors above waterline	Placing anchor: 16.45 €/m **Total**: 16.45 €/m anchor	Placing anchor: 180 kg/m **Total**: 180 kg/m anchor
Underwater anchors	Placing underwater anchor: 16.45 €/m **Total**: 16.45 €/m anchor	Placing underwater anchor: 180 kg/m **Total**: 180 kg/m anchor

Table 3.4: Sustainable data per structural adjustment

Table 3.5 below includes the data for the total cost per structural adjustment, which was compiled in consultation with a cost expert of BAM. Again, there exists uncertainty in the data, and the generic values have been compiled based on a number of assumptions that differ per adjustment. However, this is justified as the primary objective remains to highlight the differences between the adjustments rather than using the most accurate values. In addition, the choice was made to focus on direct implementation costs which include material and equipment costs as mentioned before. Other variable costs, such as time-dependent processes or personnel costs, are excluded as they could not be made generic because these costs depend on project-specific factors. For costs, certain side activities should also be included. The table therefore includes a total cost line for each adjustment for clarity. As this total depends on several materials and associated volume units, the materials concerned are indicated in abbreviations. For example, the material of a sheet pile is denoted as 's.p.'. For the adjustments 'adding BIMS' and 'placing colloidal concrete', the same steps apply. In addition to placing the considered materials, soil also needs to be removed at additional costs. For the anchor adjustments, no additional steps need to be included as each construction step is already included in the price. For the extension of the sheet pile, however, some side activities have to be taken into account again. These are that the existing capping beam must first be removed and reinstalled as the final step in the construction process. In addition, mobilisation and demobilisation costs of the machinery used have to be taken into account, which are assumed to be constant costs, which also applies to the driving machine. For the driving process, additional costs should be included for the additional number of square metres driven into the ground. Finally, welding costs should also be included for the additional material welded along the length of the sheet pile wall.

Structural adjustment	Costs
Adding BIMS	Placing BIMS: 110.50 €/m^3 Removing soil: 10 €/m^3 **Total**: 120 €/m^3 BIMS
Extending Sheet Pile	Sheet pile (s.p.) material: 1200 €/ton Removing capping beam (c.b.): 50 €/m Placing capping beam (c.b.): 60 €/m Mob & Demob machines: €5000 Driving machine: €3500 Driving process: 30 €/m^2 Welding: €200/m **Total**: 1200 €/ton s.p. + 110 €/m c.b. + €8500 + 30 €/m^2 s.p. + 200 €/m length s.p.
Placing colloidal concrete	Colloidal concrete: 195 €/m^3 Removing soil: 10 €/m^3 **Total**: 205 €/m^3 colloidal concrete
Anchor above waterline	Placing anchor: 139 €/m **Total**: 139 €/m anchor
Underwater anchor	Placing underwater anchor: 2*139 €/m **Total**: 278 €/m anchor

Table 3.5: Financial data per structural adjustment

– **Individual objective functions**: The objectives that are being used in this project are minimising the ECI-price, CO2 emissions and total costs. These are calculated by adding up the individual contributions of each adjustment. Here, only the applicable adjustments leading to a design that satisfies are included, taking into account the binary variables as well. Equations 3.3, 3.4 and 3.5 show them in formula form, respectively:

$$\min .ECI = \sum ECI_i * x_i * x_{ii} \tag{3.3}$$

$$\min .CO2 = \sum CO2_i * x_i * x_{ii} \tag{3.4}$$

$$\min .Costs = \sum Costs_i * x_i * x_{ii} \tag{3.5}$$

in which ECI_i, $CO2_i$ and $Costs_i$ represent the data per adjustment that tables 3.4 and 3.5 showed, x_i represents the amount of each specific adjustment which depends on the dimensions per adjustment and x_{ii} represents the binary variables.

To calculate each objective, the required amount of each considered adjustment must first be calculated, depending on the optimised dimensions. In addition, certain side activities of adding adjustments also include certain materials or steps whose volumes need to be calculated. For example, when the existing capping beam of a sheet pile should be removed and placed again. The volume of a BIMS layer can be calculated using equation 3.6:

$$V_{BIMS} = ((T_{sp} - 1) - x_1) * L_{sp} * H_{ret.} \tag{3.6}$$

in which T_{sp} is the top level of the sheet pile [m], x_1 is the optimised bottom level of the BIMS soil layer [m], L_{sp} is the total length of the sheet pile wall [m] and $H_{ret.}$ is the retaining height of the sheet pile [m]. The width of the BIMS layer is defined as equal to the retaining height of the sheet pile wall. For the quay walls considered, this is a valid approximation of the active wedge on the active side of the quay wall. This approximation is based on that the active wedge starts from the second point where the shear force equals 0 below the surface on the passive side. From that point, a line goes up at an angle of 30 degrees, resulting in the active wedge. The area of the extra sheet pile material that is welded on the existing sheet pile can be calculated according equation 3.7:

$$A_{s.p.} = (B_{sp} - x_2) * L_{sp}/2 \tag{3.7}$$

in which B_{sp} is the bottom level of the existing sheet pile [m] and x_2 is the optimised bottom level of the extra sheet pile material [m]. The total length of the sheet piling is divided by 2, as the planks are staggered. The volume of the colloidal concrete layer can be calculated following equation 3.8:

$$V_{C.C} = (E_L - x_3) * L_{sp} * W_{channel} \tag{3.8}$$

in which E_L is the future excavation level [m], x_3 is the optimised bottom level of the colloidal concrete layer [m] and $W_{channel}$ is the width of the water [m] that the sheet pile faces. In equation 3.9, the total anchor length is calculated, which is the length of all anchors together:

$$L_{anchors;tot} = x_4 * N_{anchors} \tag{3.9}$$

in which x_4 is the length [m] of the anchors above the waterline and $N_{anchors}$ are the amount of anchors that are placed, which can be calculated according equation 3.10:

$$N_{anchors} = \frac{L_{sp}}{c.t.c.} \tag{3.10}$$

in which $c.t.c.$ is the center-to-center distance [m] between the anchors that are placed. Normally, this would be determined based on specific quay wall conditions, but since a generic tool is developed, this distance is fixed at 2.80 metres, based on common dimensions of sheet pile walls. The total amount of anchors placed is rounded down to whole numbers, as only whole anchors can be placed. In equation 3.11, the formula for the length of all underwater anchors is stated:

$$L_{uw-anchors;tot} = L_{UWanchor} * N_{anchors} \tag{3.11}$$

in which $L_{UWanchor}$ [m] is depending on x_5 [m] and calculated by equation 3.2 and $N_{anchors}$ can be calculated by the same formula for the anchors that are placed above the waterline (3.10). Lastly, assuming that the shape of a capping beam is rectangular, the volume of capping beams can be calculated according equation 3.12:

$$V_{c.b.} = L_{sp} * W_{c.b.} * H_{c.b.} \tag{3.12}$$

in which $W_{c.b.}$ is the width [mm] and $H_{c.b.}$ is the height of a capping beam [mm]. For the industrial port of Tilburg, these are set to 410 mm and 100 mm.

- **Resulting objective function**: After formulating the three individual objectives, the ECI price, CO2 emissions and costs, the tool combines these three objectives into a single objective function. Ultimately, this single objective function is able to calculate the aggregated preference score of each solution. It starts by calculating the preference score for each individual objective, and from these, the aggregated preference score is derived. This score is influenced by user-defined weights for each objective. The Genetic Algorithm (GA) receives the aggregated score as its input to assess the performance of each solution. Should a set of design variables emerge that improves the aggregated preference score, the GA iteratively refines these variables in subsequent generations. This iterative process allows the GA to converge towards a solution containing a maximised aggregated preference score.
- **Constraints**: In an optimisation problem, constraints should also be added. These are certain conditions that the solution must satisfy. These may include, for example, that the costs must be below a predetermined maximum, or that the volumes of each adaptation must be below a maximum. The constraints should include the variables of the model and they should be added as *inequality* constraints, meaning that they should be of the form $c(x) \leq 0$. For this project, four constraints are added to the model which this section explains below:
  - **Maximum costs**: Equation 3.13 shows the first constraint $c1$ that is added to the model, which includes the maximum costs. The total costs that are calculated by using equation 3.5, should in any case be below the total costs of the new sheet pile construction $Costs_{new}$, as this is the alternative for the reinforcement situation.

$$c1 = \sum Costs_i * x_i * x_{ii} - Costs_{new} \leq 0 \tag{3.13}$$

  - **Maximum ECI-price**: Equation 3.14 shows the second constraint $c2$ that is added to the model, which includes the maximum ECI-price. It should hold that the total ECI-price of the reinforcement situation should be lower than 75% of the total ECI-price of the new sheet sheet pile construction ECI_{new}. This is because in most construction projects within infrastructure, a MEAT discount is given when a design can be created within 75% of the ECI-price of the reference design. Since for this project it is a generic tool where no specific reference design can be adopted, the new construction situation in this case counts as the reference design. Therefore, the maximum of 75% applies.

$$c2 = \sum ECI_i * x_i * x_{ii} - 0.75 * ECI_{new} \leq 0 \tag{3.14}$$

  - **Failure resistant**: The third constraint $c3$ that is added to the model, includes the check whether the configuration of adjustments is resulting in a design that satisfies. Equation 3.15 shows this constraint, in which the unity check of the maximum deformation UC_D is calculated by performing a Dsheet calculation. Although the constraint reflects as if only the unity check on the maximum deflection is calculated, it is important to mention that the sheet pile is tested for each failure mechanism that section 2.1.3 includes. However, it is set such that if no failure mechanism occurs, the UC_D (which then is below 1) is used as a value to create an inequality constraint. However, when one of the failure mechanisms (e.g. the anchor fails, no stable wall) occurs, an arbitrary value greater than 1 will be given to UC_D, so that the constraint is not met. As a result, the GA knows that this configuration of adjustments does not satisfy, so it is not included as a feasible solution. As section 3.4.2 will explain in more detail, performing multiple Dsheet calculations takes a lot of computational time. Thus, it is known that using $c3$ is critical for the computational time of the model, as each configuration of adjustments that is created by the GA will be calculated in Dsheet. However, for the feasibility of the solutions, it is important to include this constraint because if the constraint was missing, a solution could be created that leads to a design which doesn't satisfy.

$$c3 = UC_D - 1 \leq 0 \tag{3.15}$$

  - **Minimum binary variables**: The fourth constraint $c4$ that is added to the model arises because binary variables are added to the model. Equation 3.16 shows this constraint and it holds that at least one of the structural adjustment should be added to the sheet pile. Since an inequality constraint must be created, the binary variables of a given configuration must be summed up and multiplied by -1, after which 0.9 must be added. If no adjustment is used, $c4$ would equal 0.9, so the constraint is not satisfied and no feasible solutions are found. However, if one or more adjustments are used, a negative value for $c4$ is returned, so the constraint is met. It is necessary to use this constraint because without it, the preferred result would be that no adjustment is used, resulting in no ECI-price, CO2 emissions or costs at all.

$$c4 = \sum(-1 * x_{ii}) + 0.9 \leq 0 \tag{3.16}$$

3.4.2. Set-up of the Genetic Algorithm

As mentioned before, the Preferendus Tool makes use of a Genetic Algorithm [30] which section 2.4 explained. To tailor the GA to specific needs of a certain project, different settings can be set to find the optimal solution within the system boundaries. This section includes these settings and explains how they are set for this project. Table 3.6 presents them as overview.

- **Number of runs**: These are denoted by N_{runs} and determine how often the GA is run. Since a GA is stochastic from nature, it could occur that the solution that is found differs per run. It is therefore important that the GA is runned more than once, to be able to compare the results with each other. However, because of the integration with Dsheet the computational time of the GA is significantly increased and therefore the number of runs, N_{runs}, is set to two.
- **Number of bits**: These are denoted by N_{bits} and serve as digital encoding of potential solutions in the search space. In terms of the evolution theory, the length of the bit string is also known as the chromosome length. This length determines the resolution of the solutions being explored. A longer bit string therefore allows for a finer representation, but it also increases the complexity of the search, potentially requiring more iterations for convergence. Conversely, a shorter bit string simplifies the search but might miss finer details. Since the potential structural adjustments all vary 0.5 m in practice, the number of bits N_{bits} is set to four.
- **Population size**: Is denoted by N_{pop} and determines the number of potential solutions (or individuals) being considered in a given generation. Larger populations offer a broader search space and enhance diversity, which can be advantageous in exploring a wider array of solutions and avoiding fast convergence to results that are not optimal. However, larger populations come with increased computational time and require more evaluations per generation. On the other hand, smaller populations are computationally more efficient but run the risk of insufficient diversity, possibly missing out on optimised solutions. Since the bounds of the variables in this model are defined relatively close to each other and the number of bits is set to four, the population size need not be large. Therefore, the population size N_{pop} is set to ten.
- **Max. number of iterations**: Is denoted by N_{iter} and determines how many times the algorithm will maximally select, crossover, mutate, and potentially replace individuals to form new populations. More iterations generally allow for greater exploration and refinement of the solution space, enhancing the chances of finding optimal or near-optimal solutions. However, too many iterations can lead to over-exploitation, where the algorithm keeps refining a local optimum without exploring other potentially better regions of the search space. Additionally, many iterations increase computational time, especially because of the integration with Dsheet, without necessarily providing significant improvements in solution quality. Therefore, for this project the maximum number of iterations N_{iter} is set to fifteen.
- **Max. stall**: Represents the number of consecutive generations without a noticeable improvement in the best solution. If the GA reaches this limit, it can be an indicator that the algorithm might be stuck in a local optimum and not making significant progress towards finding a better solution. Setting a max. stall therefore serves as a stopping criterion, reducing computational time. However, setting it too low might stop the algorithm before it has had the opportunity to explore the entire solution space, while setting it too high might lead to excessive computational

time in cases where no significant improvement is likely. For this project, a max stall is therefore set to ten, so that it should be possible to find the preferred configuration within the maximum of fifteen iterations.

- **Cross-over rate**: Is denoted by R_{cross} and indicates the chance that the crossover process will be used on selected parent solutions as the algorithm progresses. The cross-over rate should be a value between 1 and 0. A value of 1 implies that crossover is always executed when parents are chosen, while a value of 0 means crossover never occurs. For instance, if it is set to 0.2, there's a 20% chance that crossover will be performed on a pair of selected parents in any given generation. Conversely, if R_{cross} is set to 0.8, there's an 80% chance of crossover occurring. This parameter is important to control the balance between exploration (generating diverse solutions) and exploitation (refining existing solutions) within the algorithm [36]. A high R_{cross} promotes the creation of new combinations of genetic material, potentially aiding in the discovery of new solution regions, whereas a lower R_{cross} aims to improve existing solutions. Since the GA is set to not require many iterations due to the excessive computational time, the R_{cross} is set to 0.8 for this project, to explore more combinations of solutions.

Setting	Value
N_{runs}	2
N_{bits}	4
N_{pop}	10
N_{iter}	15
Max. stall	10
R_{cross}	0.8

Table 3.6: Settings of GA

In general, the settings of the GA are important to control the total computational time of the model. Since for each individual of an iteration of every run a Dsheet sum has to be completed, the computational time can quickly increase. The amount of Dsheet sums that are calculated by the GA can be calculated using equation 3.17 below. Using the settings stated that table 3.6 included while the average computational time of a Dsheet sum is 30 seconds, the total computational time could rise up to 2.5 hours. Since the adjustments are also tested individually before the GA is executed, the total calculation time could even rise up to 3 hours. To reduce this time, it is inserted in the GA that if in a solution all binary variables are equal to 0, the solution can be skipped and no Dsheet sum has to be calculated and evaluated.

$$N_{sums} = N_{pop} * N_{iter} * N_{runs} \tag{3.17}$$

3.5. New Sheet Pile Construction

To determine the potential reductions in ECI-price, CO2 emissions, and costs achieved by reinforcing rather than renewing quay walls, a renewal situation is created for each case study. In this situation, the existing sheet pile is completely replaced with a new sheet pile wall. This situation serves as a reference design for the reinforcement situations. Since this process is assumed to be the same for each sheet pile, the same implementation steps are considered for each case study. Appendix A shows the process of renewing the sheet pile walls and the data that is used to calculate the total resulting ECI-price, CO2 emissions and costs of each case. Chapter 4 discusses the specific values obtained for each case study and the percentage reductions achievable by applying the structural adjustments instead of renewing the quay walls.

3.6. Flow-Chart

To clearly visualise all steps when using the tool and the interaction between them, figure 3.2 shows a flow-chart of the tool. It includes all steps and needs covered in the previous sections. Although the yellow blocks in the flow-chart indicate as if certain decisions need to be made within the tool, it is an automatic tool that doesn’t need any modifications when all input data is set. This includes both the sheet pile specific input, such as the geotechnical conditions, anchor data, geometry information and the loads that are acting on the sheet pile wall, and the optimisation input such as the pre-defined weights of the stakeholders and the GA settings as section 3.4.2 explained.

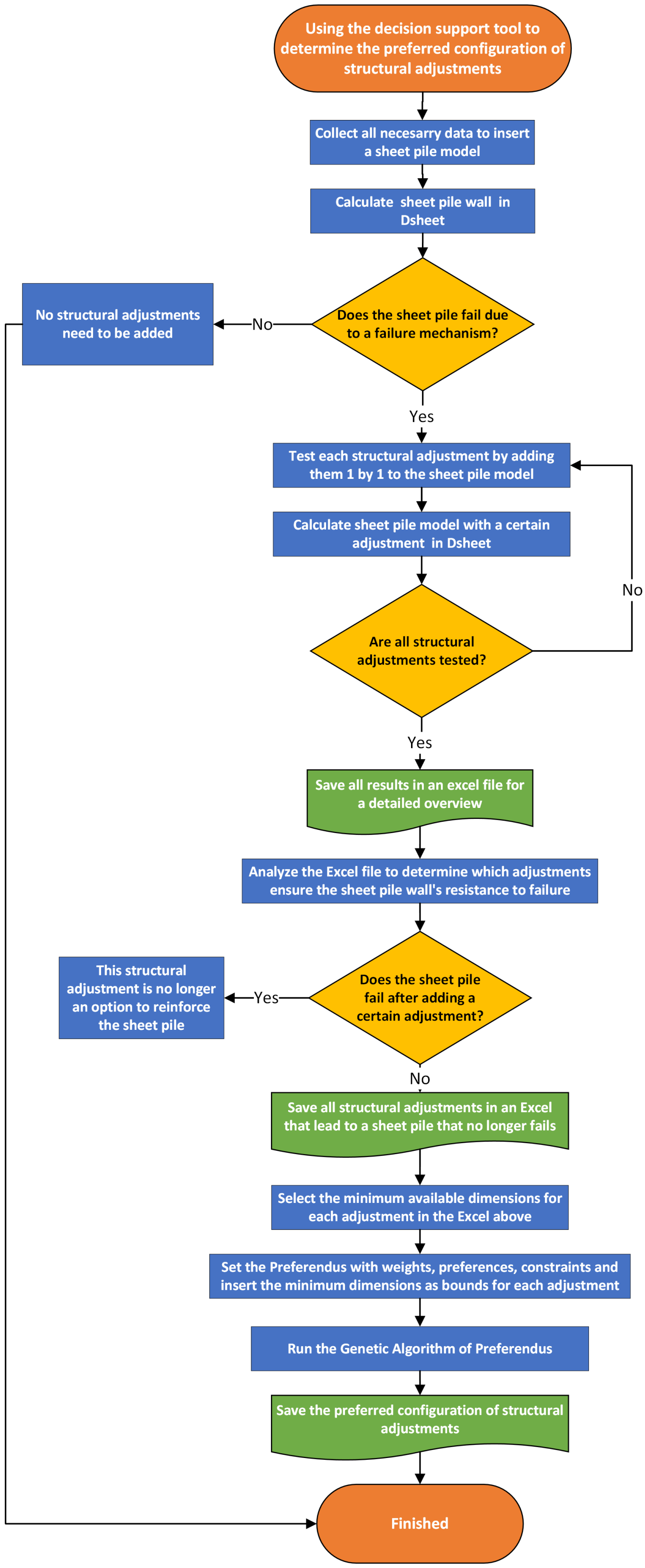


Figure 3.2: Flow-chart of decision support tool

4
Case Studies Results

This chapter commences with a brief introduction of the quay walls to which the tool is applied, which are the case studies of this project. It then separately addresses each case, by following the same steps. For each case, the first step is to verify the need for adjustments to the quay wall to withstand the future water bottom level. This involves comparing the results from the tool, PLAXIS and BLUM with each other. The compared results are the considered unity checks for the bending moment, anchor capacity, shear force and maximum displacement and the overall stability of the sheet pile wall. Based on these results, the active failure mechanism is determined. The next step is to collect all solutions that could lead to a design that satisfies. This includes both the two obtained optimised configurations resulting from the GA, as well as the individual applicable adjustments and the new sheet pile structure. Ultimately, the preferred solution should be determined from one of these options. For each solution, Tetra is used to determine the aggregated preference score. As the GA only compares the output of the two runs performed, it is necessary to enter all options manually and together in Tetra. The solution with a maximum aggregated preference score of 100 is determined as the theoretically maximum preferred configuration of structural adjustments. The next step is to calculate the reduction rates in ECI-price, CO2 emissions and costs of the preferred configuration compared to the scenario of installing a new sheet pile wall. To visualise these results, each case study presents the preference curve of each stakeholder in which each solution is plotted as well. Finally, the preferred configuration is tested in PLAXIS to verify that this configuration results in a design that satisfies.

4.1. Case Studies Introduction

The developed tool will be applied on three case studies. These will be three steel sheet pile walls which all are in the industrial harbour Loven in Tilburg. Figure 4.1 shows a map of this harbour and indicates which quay wall segments are considered. In total, there are 32 different segments of quay walls in this harbour, accounting for approximately 3.8 kilometres. Of these 32 segments, three were chosen to apply the tool on. These three segments were selected because the municipality of Tilburg provided accurate data for these three segments and each segment was eligible for renewal or reinforcement. Appendix B includes a cross-section of each sheet pile, the present soil profiles and associated soil parameters, sheet pile specifications, geometric specifications and the loads acting on each quay wall.

4.2. Quay Wall Van Casteren

4.2.1. Verification of Failure

Table 4.1 includes the obtained values for the maximum bending moment, anchor force, shear force and displacement and the resulting unity checks for quay wall Van Casteren. These values are calculated for both the ULS and SLS and for both the current situation and the future situation. The future situation accounts for the situation in which the future excavation is applied and the current top loads are activated again. BLUM's method will only be used for the SLS because of its limitations. Besides, it doesn't calculate the active shear force or displacements. As section 2.1.3 explained, the displacement of the sheet pile is only calculated in the SLS. The table shows that the sheet pile will fail in the future

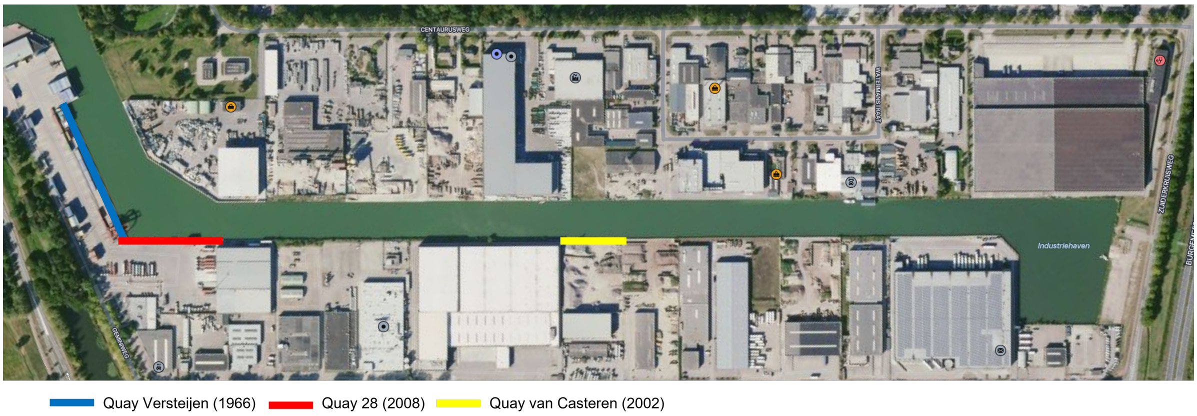


Figure 4.1: Industrial harbour Loven in Tilburg and considered quay wall segments [37]

situation. Results of the tool, which uses Dsheet for the sheet pile calculations, show that the sheet pile wall becomes unstable in the ULS of the future situation. In PLAXIS it is found that the anchor will fail in ULS of the future situation, since the unity check of the anchor capacity becomes larger than 1. Since both by the tool and by PLAXIS it is found that failure will occur, it is verified that the sheet pile needs to be adjusted or renewed to withstand future excavation. Differences exist between the obtained values of both methods, however these could have been expected as section 2.1.4 already described that both programs use different calculation methods. Next to that, the goal of calculating this sheet pile by multiple methods is to verify that for each method it holds that the sheet pile doesn't satisfy in the future situation rather than to calculate exactly the same values.

	ULS		**SLS**		
	Tool (Dsheet)	**PLAXIS**	**Tool (Dsheet)**	**PLAXIS**	**BLUM**
Calculated	**Current Situation**		**Current Situation**		
Max. Moment [kNm/m]	131.03	129.50	80.09	116.10	118.00
UC_M	**0.55**	**0.55**	**0.38**	**0.49**	**0.50**
Anchor Force [kN/m]	171.35	154.04	127.91	138.34	104.70
UC_A	**0.92**	**0.82**	**0.68**	**0.74**	**0.56**
Shear Force [kN/m]	131.09	120.60	97.70	105.80	-
UC_V	**0.23**	**0.21**	**0.17**	**0.19**	-
Displacement [mm]	-	-	11.6	27.13	-
UC_D	-	-	**0.24**	**0.57**	-
Calculated	**Future Situation**		**Future Situation**		
Max. Moment [kNm/m]	Sheet pile unstable	233.10	96.49	150.20	138.50
UC_M	-	**0.98**	**0.41**	**0.63**	**0.58**
Anchor Force [kN/m]	Sheet pile unstable	207.94	141.81	153.75	112.80
UC_A	-	**1.11**	**0.76**	**0.82**	**0.60**
Shear Force [kN/m]	Sheet pile unstable	167.10	106.13	123.20	-
UC_V	-	**0.29**	**0.19**	**0.22**	-
Displacement [mm]	-	-	16.6	39.02	-
UC_D	-	-	**0.31**	**0.74**	-

Table 4.1: Calculations of current and future situation in both the ULS and SLS of quay wall Van Casteren

4.2.2. Failure Mechanism

To gain more understanding of which adjustments are expected to work on the sheet pile, the failure mechanism of quay wall Van Casteren is established first. Section 2.1.3 described the possible failure mechanisms considered for this project. For this case, the tool establishes that the active failure mechanism is soil failure, leading to an unstable sheet pile wall. This means that if the ground level is lowered in the future situation without making adjustments, the entire sheet pile will slide due to the missing horizontal force balance. However, the results in PLAXIS showed that the anchor will fail in the future situation, which is known as the failure of the support mechanism. As the tool tests the considered adjustments in Dsheet, it is expected that the solutions that will be found will be able to make the sheet pile stable again rather than improve the anchor capacity. It can therefore be determined that failure of the soil is the active failure mechanism for quay wall Van Casteren. Nevertheless, the preferred solution from the tool will also be verified in PLAXIS to see if the solution contributes to relieving the anchor.

4.2.3. Results

Table 4.2 shows the resulting aggregated preference score, the objective values and individual preference score of all possible solutions for quay wall van Casteren. These include both the optimised solutions of the GA, denoted as 'IMAP Run 1 & 2' in the table, the individual applicable adjustments and the new sheet pile situation. For this quay wall, the tool finds that three adjustment are applicable to create a design that satisfies. The minimal dimensions that are found differ per adjustment, as section 3.3 explained. The applicable adjustments and the corresponding dimensions for quay wall Van Casteren are as follows:

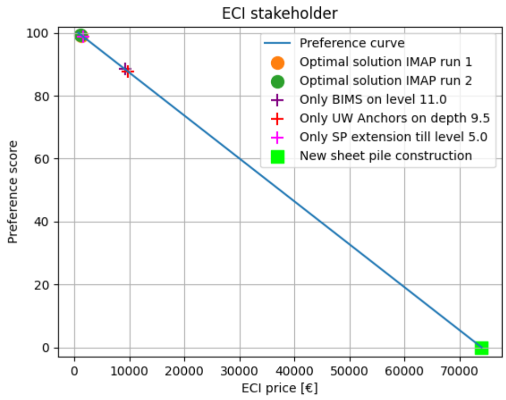
1. **Placing UW anchors**: The minimum point of engagement level for UW anchors should be 9.5 +m N.A.P. Using equation 3.2 it is found that these anchors should then be of length 11.5 m.
2. **Adding BIMS as soil layer**: The minimum bottom level for a BIMS layer should be 11.0 +m N.A.P. With an upper level of 12.5 +m N.A.P., which is 1 metre below the top soil layer, it is obtained that the BIMS layer should be 1.5 m thick.
3. **Extending Sheet Pile**: The minimum bottom level because of the sheet pile extension should be 5.0 +m N.A.P. This would result in extending the sheet pile by 0.5 m, which leads in extra yielded material of 36.1 m^2.

As the flowchart in section 3.6 showed, the applicable adjustments are sent to the GA as design variables. Combined with the binary variable per adjustment, the optimised configuration of these design variables is sought by the tool. Since the GA is set to be run twice, two solutions are obtained whose aggregated preference score is maximised. As table 4.2 shows, for both runs the solution found was to extend the sheet pile wall. While the GA allowed some slack in the bounds of each adjustment to find an optimised combination of adjustments, it determined that the theoretically maximum preferred configuration would be to only extend the sheet pile to 5.16 +m N.A.P. Although this configuration has the maximum aggregated preference score 100, steel sheet pile extensions are practically carried out in 0.5 m increments. This would amount to extending the sheet pile to 5.0 +m N.A.P. As a result, extending the sheet pile to 5.0 +m NAP is determined as the preferred configuration to reinforce quay wall Van Casteren. Consequently, it is found that by choosing this reinforcement over renewing the entire sheet pile, a 98% reduction in ECI-price, 98% in CO2 emissions and 94% in costs can be obtained.

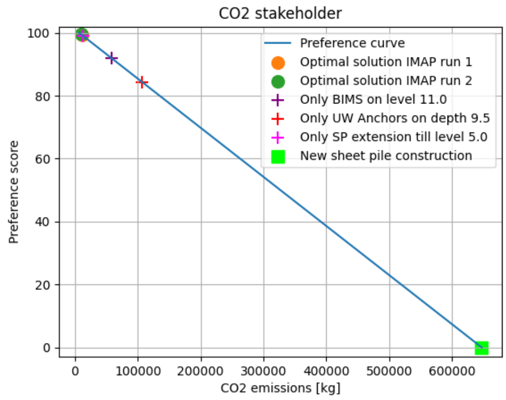
Configuration	Agg. Pref. Score	UW Anchors Depth	BIMS layer Bottom Level	SP-extension Bottom Level	ECI-price [€]	CO2 [kg]	Costs [€]	Pref. ECI	Pref. CO2	Pref. Costs
IMAP Run 2	**100,00**	-	-	5,16 +m N.A.P	1.180	9.785	35.535	99,40	99,48	89,06
IMAP Run 1	**99,75**	-	-	5,09 +m N.A.P	1.370	11.230	36.250	99,14	99,26	88,80
SP-extension	**99,37**	-	-	5,0 +m N.A.P	1.650	13.405	37.320	98,76	98,92	88,41
BIMS	**86,54**	-	11,0 +m N.A.P		9.185	58.545	145.985	88,47	91,88	62,53
UW Anchors	**82,33**	9,5 +m N.A.P	-	-	9.755	106.750	164.875	87,69	84,36	58,61
New sheet pile	**0,00**	-	-	-	74.000	647.500	650.000	0	0	0

Table 4.2: Aggregated Preference Scores for each configuration of quay wall Van Casteren

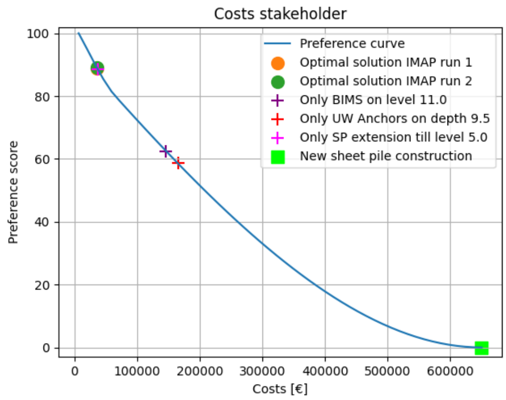
To visualise the differences in preference scores between each configuration, figure 4.2 shows the preference curves of each stakeholder in which all possible solutions are plotted. These preference curves are created by using the values as section 3.4.1 described. Based on these curves and on the weights of each stakeholder, the individual preference scores of each objective is calculated, shown in table 4.2 and hence plotted. As expected by the results in the tabel, the plots show that both the IMAP runs and the SP extension configurations have the highest preference score for each target. It is also noticeable that adding BIMS or placing UW anchors are relatively close in terms of ECI-price and cost, but there is a difference for CO2 emissions. Finally, the figure also shows the new sheet pile construction which is the least favourable option for each objective and therefore scores 0 for each objective.



(a) ECI-price stakeholder



(b) CO2 emissions stakeholder



(c) Costs stakeholder

Figure 4.2: Preference curves and applicable solutions for quay wall Van Casteren

4.2.4. Verification of Optimised Adjustments

To verify the preferred configuration of extending the sheet piling by 0.5 m to bottom level 5.0 +m N.A.P, a PLAXIS model was created that includes this configuration to compare its results with the tool results. Table 4.3 shows the results of both. Again, calculations are included for both the ULS and SLS. It stands out that the unity check of the anchor is 0.98 when the tool calculates it, and that the PLAXIS model calculates it to be 1.02. While the calculated values are thus not much different from each other, a consequence of this is that according to the tool the adjustment leads to a design that satisfies, but according to the PLAXIS model it doesn't. This can be explained by stating that the tool iterates till the minimum amount per adjustment is found which leads to a feasible design. As a result, unity checks may be calculated as close to 1 as possible to arrive at minimum ECI-price, CO2 emissions and costs. If small differences in calculated values are then obtained by the PLAXIS model, this can lead to a unity check that is slightly not met as is the case here. However, because the difference is small and it is a rule of thumb among constructors that a unity check may be overridden by 3%, there is no need to attach any consequences here. Besides, for all other values the table shows that every unity check is achieved in both the SLS and ULS by both the tool and the PLAXIS model. It is therefore justified to state that the preferred configuration has been verified by the PLAXIS model.

	ULS		SLS	
	Tool (Dsheet)	PLAXIS	Tool (Dsheet)	PLAXIS
Calculated	Future Situation Adjustments		Future Situation Adjustments	
Max. Moment [kNm/m]	155.94	204.00	93.05	143.0
UC_M	**0.66**	**0.86**	**0.39**	**0.60**
Anchor Force [kN/m]	183.55	190.37	140.60	147.15
UC_A	**0.98**	**1.02**	**0.75**	**0.79**
Shear Force [kN/m]	140.14	148.90	104.64	117.10
UC_V	**0.25**	**0.26**	**0.18**	**0.21**
Displacement [mm]	-	-	16.10	30.95
UC_D	**-**	**-**	**0.30**	**0.59**

Table 4.3: Calculations of future situation with optimised adjustments in both the ULS and SLS of quay wall Van Casteren

4.3. Quay Wall 28

For this case, a modification had to be made to the PLAXIS model to avoid local failure of the soil at surface level. The local surface load of 350 kPa, which Appendix B shows for this quay wall, leads to large deformations and failure of the top soil, as would be expected in reality. To still be able to compare the PLAXIS results with the results of the tool that are obtained by Dsheet, a concrete layer is added to the PLAXIS model for the load distribution. As Dsheet only translates this surface load to a resulting force on the modelled sheet pile, this phenomenon of local failure at surface level does not occur with Dsheet. Although adding the concrete layer can affect the comparison of results, it does make it possible to verify whether the quay can withstand the future situation.

4.3.1. Verification of Failure

Table 4.4 shows the calculated values and the resulting unity checks of quay wall 28 by the tool, PLAXIS and BLUM's method for the current and future situation. The table shows that the sheet pile will fail in the ULS of the future situation, as a unity check of 1.08 for the anchor capacity is obtained indicating that the anchor will fail. Next to that, the calculation of the PLAXIS model failed during that stage, indicating that a failure mechanism is active. It is thus verified that the sheet pile needs adjustments to withstand the future deepening of the water bottom, based on the ULS of the future situation.

	ULS		SLS		
	Tool (Dsheet)	PLAXIS	Tool (Dsheet)	PLAXIS	BLUM
Calculated	Current Situation		Current Situation		
Max. Moment [kNm/m]	232.54	131.50	148.51	108.10	229.00
UC_M	**0.32**	**0.18**	**0.21**	**0.15**	**0.32**
Anchor Force [kN/m]	229.09	137.15	165.07	117.44	192.90
UC_A	**0.97**	**0.58**	**0.70**	**0.50**	**0.81**
Shear Force [kN/m]	197.68	111.70	143.93	95.16	-
UC_V	**0.15**	**0.09**	**0.11**	**0.07**	-
Displacement [mm]	-	-	19.50	19.20	-
UC_D	-	-	**0.43**	**0.43**	-
Calculated	**Future Situation**		**Future Situation**		
Max. Moment [kNm/m]	293.26	Calculation failed	191.26	135.50	281.30
UC_M	**0.41**	-	**0.27**	**0.19**	**0.39**
Anchor Force [kN/m]	256.45	Calculation failed	195.60	137.26	213.30
UC_A	**1.08**	-	**0.83**	**0.58**	**0.90**
Shear Force [kN/m]	219.56	Calculation failed	165.49	114.40	-
UC_V	**0.17**	-	**0.13**	**0.09**	-
Displacement [mm]	-	-	27.1	27.52	-
UC_D	-	-	**0.51**	**0.52**	-

Table 4.4: Calculations of current and future situation of quay wall 28

4.3.2. Failure Mechanism

For this case, the tool establishes that the active failure mechanism is the failure of the support mechanism, as the anchor will collapse in the ULS of the future situation. For the PLAXIS model it is not directly clear which failure mechanism is active in this model, as the calculation failed in the ULS. However, when analysing the results of the PLAXIS model it is obtained that the soil body is collapsed, indicating that the failure of soil is the active failure mechanism. This is caused by the top load of 350 kPa at ground level. Since the failure mechanism of the tool is normative, it is determined that the failure of the support mechanism is the active failure mechanism for quay wall 28.

4.3.3. Results

Table 4.5 shows the resulting aggregated preference score, the objective values and individual preference score of all possible solutions for quay wall 28. This includes both the optimised solutions of the GA, the individual applicable adjustments and the new sheet pile situation. For this quay wall, three adjustments can be applied to create a sheet pile design that satisfies. The applicable adjustments and the corresponding dimensions for quay wall 28 are as follows:

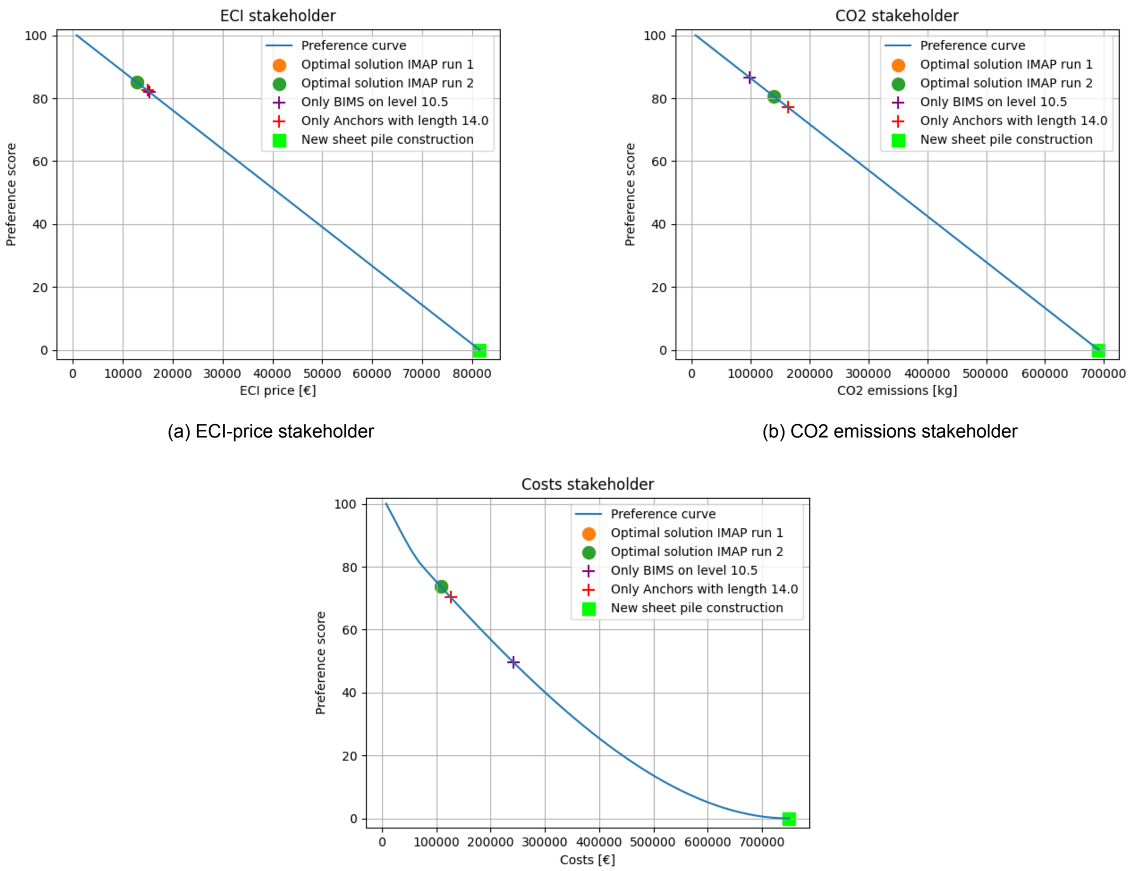
1. **Placing AW anchors**: The minimum length for the anchors above the waterline should be 14.0 metres. These should be placed on point of engament level 13.0 +m N.A.P, which is 0.5 m above the waterline.
2. **Adding BIMS as soil layer**: The minimum bottom level for a BIMS layer should be 10.50 +m N.A.P. With an upper level of 12.5 +m N.A.P., which is 1 metre below the top soil layer, it is obtained that the BIMS layer should be 2.0 m thick.
3. **Placing UW anchors**: The minimum point of engagement level for the UW anchors should be 9.50 +m N.A.P. Using equation 3.2 it is found that these anchors should then be 7 metres long.

As stated before, it is set that if both AW anchors and UW anchors are found to be applicable as individual adjustments, the AW anchors will be sent to the GA and the UW anchors will be left out of consideration as possible adjustment. This is because if it turns out to be possible to install AW anchors, this is a valid option to consider as this is currently one of the most common ways of reinforcing a quay wall. Besides, in practice it is not possible to apply them both. The table below shows that both runs of the GA obtained the same optimised solution, which is placing anchors above the waterline of 12 metres long. Therefore, both runs obtained the best aggregated preference score of 100. It is notable that when the above water anchors are tested individually, the tool indicates that they should be at least 14 metres long. This is due to the bounds set, as the GA allowed a slack of 2 metres with respect to the minimum required length in order to search for the preferred combination of adjustments. Despite this, the tool identifies placing only above water anchors as the preferred configuration, indicating that even anchors of 12 metres would create a satisfactory design. However, if the anchors were to be implemented in practice, a length of 14 metres would be chosen. This is because there should be at least one metre space between the top level of the solid sand layer and start of the grout body when used as individual adjustment, as was indicated in formula 3.1. Based on this, it can be determined that the preferred configuration to reinforce quay 28 is to install anchors above water that are 14 metres long. As a result, it is found that by choosing this reinforcement over renewing the entire sheet pile, a 82% reduction in ECI-price, 76% in CO2 emissions and 83% in costs can be obtained. Furthermore, the table also highlights that the solution of adding BIMS as soil layer has an aggregated preference score of 94.75, which is just approximately 1% less preferred than adding the AW anchors. Looking at the individual target preference score, adding BIMS scores even better in terms of CO2 emissions. However, for costs, it scores significantly lower, ultimately resulting in a lower aggregated preference score.

Configuration	**Agg. Pref. Score**	**AW Anchors** Length	**BIMS layer** Bottom Level	**ECI-price** [€]	**CO2** [kg]	**Costs** [€]	**Pref.** ECI	**Pref.** CO2	**Pref.** Costs
IMAP Run 1	**100.00**	12,00 m	-	12.815	140.245	108.300	85,12	80,51	73,67
IMAP Run 2	**100.00**	12,00 m	-	12.815	140.245	108.300	85,12	80,51	73,67
AW anchors	**96.14**	14,00 m	-	14.955	163.620	126.350	82,48	77,09	70,28
BIMS	**94.75**	-	10,50 +m N.A.P	15.390	98.095	241.390	81,94	86,67	49,70
New sheet pile	**0.00**	-	-	81.500	691.000	750.000	0	0	0

Table 4.5: Aggregated Preference Scores for each configuration of quay wall 28

To visualise the differences in preferences between each configuration, figure 4.3 shows the preference curves of each stakeholder in which all possible configurations are plotted. These preference curves are created by using the values as section 3.4.1 described. Based on these curves and the weights of each stakeholder, the individual preference scores of each objective are calculated, shown in table 4.5 and then plotted. The ECI-price and Costs graphs reveal no unexpected findings, as the optimised solutions IMAP run 1 & 2 have the highest preference scores and the individual adjustments BIMS and the AW anchors are below those. Looking at the CO2 emissions graph however, it stands out that adding only BIMS has the highest preference score for that objective. But as the costs plot shows, it scores significantly lower than all other configurations on total costs. Eventually, this leads to a slightly lower aggregated preference score in comparison with the other configurations. Finally, the figure also shows the new sheet pile construction which is the least favourable option for each objective and therefore scores 0 for each objective.



(a) ECI-price stakeholder

(b) CO2 emissions stakeholder

(c) Costs stakeholder

Figure 4.3: Preference curves and applicable solutions for quay wall 28

4.3.4. Verification of Optimised Adjustments

To verify the preferred configuration of placing AW anchors that are 14.00 meters long, a PLAXIS model was created that includes this configuration to compare its results with the tool results. It holds again that a concrete layer was added to the PLAXIS model, to be able to calculate it. Whereas the comparison can be affected this way, it does make it possible to verify the optimised adjustments. Table 4.6 shows the results of both. Again, calculations are included for both the ULS and SLS. As the table shows, the preferred configuration has been verified by the PLAXIS model, as it was able to calculate the model now in the ULS of the future situations. In addition, all unity checks of the PLAXIS model in both the ULS and SLS are also below 1. Moreover, a unity check of 0.77 was calculated by the tool for the anchor capacity, confirming that adding new anchors relieves the existing anchors such that the design satisfies in the future situation.

	ULS		SLS	
	Tool (Dsheet)	PLAXIS	Tool (Dsheet)	PLAXIS
Calculated	**Future Situation Adjustments**		**Future Situation Adjustments**	
Max. Moment [kNm/m]	229.75	202.90	203.75	139.00
UC_M	**0.32**	**0.28**	**0.28**	**0.19**
Anchor Force 1 [kN/m]	183.17	107.36	152.64	83.98
UC_A	**0.77**	**0.45**	**0.64**	**0.35**
Anchor Force 2 [kN/m]	147.34	64.99	115.10	53.59
UC_A	**0.42**	**0.19**	**0.33**	**0.15**
Shear Force [kN/m]	253.93	128.30	209.25	110.90
UC_V	**0.19**	**0.10**	**0.16**	**0.08**
Displacement [mm]	-	-	22.2	21.30
UC_D	**-**	**-**	**0.42**	**0.40**

Table 4.6: Calculations of future situation with optimised adjustments in both the ULS and SLS of quay wall 28

4.4. Quay Wall Versteijnen

4.4.1. Verification of Failure

Table 4.7 shows the calculated values and the resulting unity checks of quay wall Versteijnen by the tool, PLAXIS and BLUM's method for the current and future situation. The table shows that the sheet pile will fail in the ULS of the future situation. This is demonstrated by the tool in which the result shows that the sheet pile becomes unstable and by the PLAXIS model whose calculation failed. Besides, a unity check of 2.19 is obtained for the total displacements by PLAXIS in the SLS of the future situation, indicating that even in the SLS the sheet pile wall already will fail if no adjustments are applied. Again, differences exist between the calculated values, but in general, except for displacements, the values are in line with each other. Moreover, the aim is again to verify the need for adjustments, rather than to achieve identical results across different methods. It is thus verified that the sheet pile needs adjustment to withstand the future deepening of the bottom level, based on the ULS of the future situation and the unity check of the displacements of PLAXIS in the SLS of the future situation.

	ULS		SLS		
	Tool (Dsheet)	PLAXIS	Tool (Dsheet)	PLAXIS	BLUM
Calculated	**Current Situation**		**Current Situation**		
Max. Moment [kNm/m]	68.08	84.91	26.14	51.38	20.10
UC_M	**0.59**	**0.74**	**0.23**	**0.45**	**0.17**
Anchor Force [kN/m]	133.28	103.62	93.96	74.18	26.30
UC_A	**0.83**	**0.64**	**0.59**	**0.46**	**0.16**
Shear Force [kN/m]	70.72	85.57	47.90	55.32	-
UC_V	**0.15**	**0.18**	**0.10**	**0.11**	-
Displacement [mm]	-	-	10.90	39.30	-
UC_D	-	-	**0.24**	**0.87**	-
Calculated	**Future Situation**		**Future Situation**		
Max. Moment [kNm/m]	Sheet pile unstable	Calculation failed	48.41	79.00	58.80
UC_M	-	-	**0.42**	**0.69**	**0.51**
Anchor Force [kN/m]	Sheet pile unstable	Calculation failed	108.33	108.48	66.90
UC_A	-	-	**0.68**	**0.68**	**0.42**
Shear Force [kN/m]	Sheet pile unstable	Calculation failed	54.13	77.49	-
UC_V	-	-	**0.11**	**0.16**	-
Displacement [mm]	-	-	21.9	115.90	-
UC_D	-	-	**0.41**	**2.19**	-

Table 4.7: Calculations of current and future situation of quay wall Versteijnen

4.4.2. Failure Mechanism

For this case, the tool establishes that the active failure mechanism is soil failure, leading to an unstable sheet pile wall. This means that if the water bottom is lowered in the future situation without making adjustments, the entire sheet pile will slide due to the missing horizontal force balance. For the PLAXIS model it is not directly clear which failure mechanism is active in this model, as the calculation failed in the ULS. However, since a unity check of 2.19 is obtained for the maximum deformations during the SLS, it can be concluded that also by the PLAXIS model the active failure mechanism is soil failure which leads to an unstable sheet pile wall. It can therefore be determined that failure of the soil is the active failure mechanism for quay wall Versteijnen.

4.4.3. Results

Table 4.8 shows the resulting aggregated preference score, the objective values and individual preference score of all possible solutions for quay wall Versteijnen. This includes both the optimised solutions of the GA, the individual applicable adjustments and the new sheet pile situation. For this quay wall, three adjustments can be applied to create a design that satisfies. The applicable adjustments and the corresponding dimensions for quay wall Versteijnen are as follows:

1. **Placing UW anchors**: The minimum point of engagement level for the UW anchors should be 9.50 +m N.A.P. Using equation 3.2 it is found that these anchors should then be 6 metres long.

2. **Adding BIMS as soil layer**: The minimum bottom level for a BIMS layer should be 12.0 +m N.A.P. With an upper level of 12.5 +m N.A.P., which is 1 metre below the top soil layer, it is obtained that the BIMS layer should only be 0.5 m thick.

3. **Extending Sheet Pile**: The minimum bottom level because of the sheet pile extension should be 4.0 +m N.A.P. This would result in extending the sheet pile by 1.5 m, which leads in extra yielded material of 139.76 m^2.

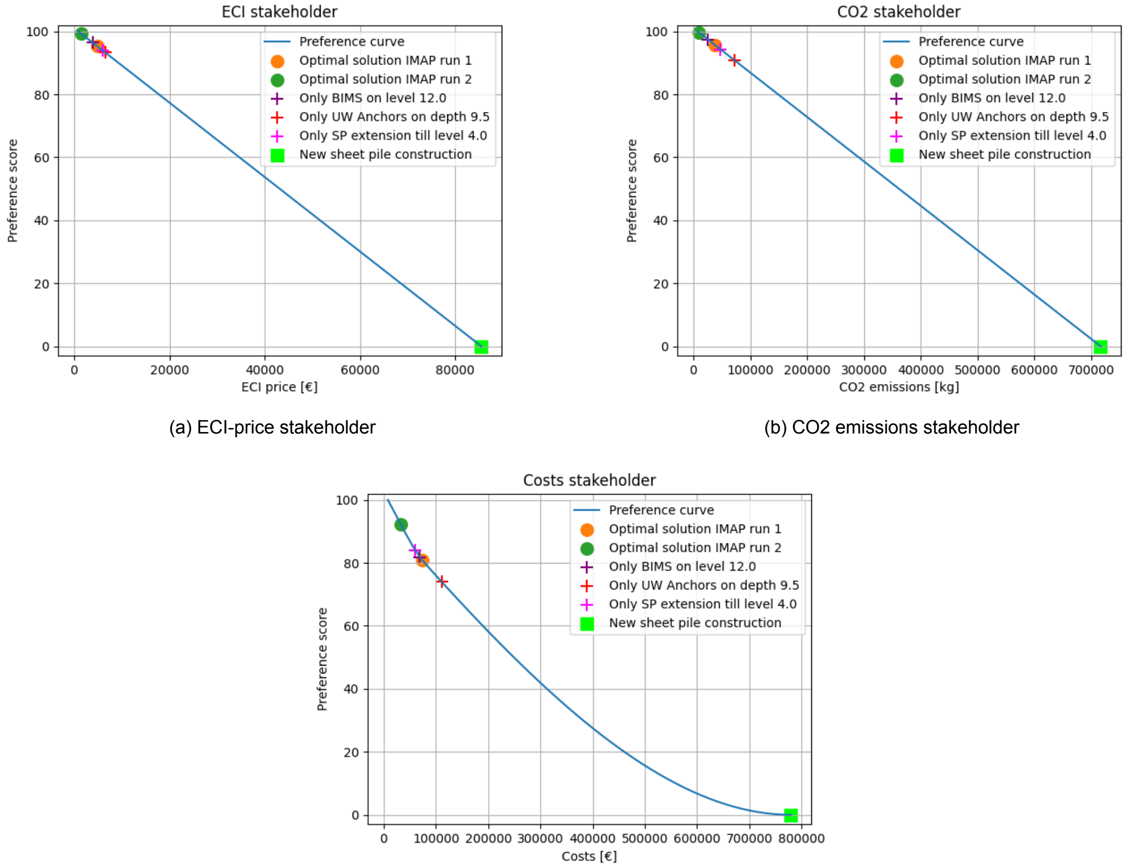
Table 4.8 shows that the two runs of the GA obtained different results. IMAP Run 1 includes two adjustments, namely adding BIMS as soil layer and extending the sheet pile. Apparently, the GA was searching for the optimised combination of both and couldn't find feasible solutions when they were tested individually. The second run, IMAP Run 2, however includes only one adjustment which is adding BIMS as soil layer. Since applying only this adjustment results in a lower ECI-price, lower CO2 emissions and lower total costs, the maximum aggregated preference score of 100 is obtained for this solution. Furthermore, it stands out that IMAP Run 2 even further optimises the bottom level of the BIMS layer than when it was tested individually. The individually tested adjustment found a required bottom level of 12.00 +m N.A.P whereas the GA found that the bottom level of the BIMS layer could even be on 12.31 +m N.A.P. Using that as bottom level, a thickness of only 0.19 m should be used. However, as adding BIMS will be in steps of 0.5 m thick in practice, the preferred configuration to reinforce quay wall Versteijnen is adding BIMS with a bottom level of 12.00 +m N.A.P. As a result, it is found that by choosing this reinforcement over renewing the entire sheet pile, a 95% reduction in ECI-price, 95% in CO2 emissions and 91% in costs can be obtained. The table also shows that the solution of extending the sheet pile to bottom level 4 +m N.A.P has a high preference score of 93.85 as well, which is approximately 1% lower than the preferred configuration. Thus, although there is a configuration with a slightly higher aggregated preference score, it appears that extending the sheet pile is a highly preferred alternative as well within the stated objectives.

To visualise the differences in preferences between each configuration, figure 4.4 shows the preference curves of each stakeholder in which all possible configurations are plotted. These preference curves are created by using the values as section 3.4.1 described. Based on these curves and on the weights of each stakeholder, the individual preference scores of each objective are calculated, shown in table 4.8 and then plotted. It stands out in the preference curves that IMAP run 1 is less preferred when considering each objective compared to the BIMS configuration and the SP extension configuration. This is because two adjustments were included in IMAP run 1, which apparently leads to a less preferred configuration than when using only BIMS or only extending the sheet pile. Furthermore it stands out that IMAP run 2 is the most preferred configuration for each objective, resulting in an aggregated preference score of 100. Besides, the ECI-price and CO2 emissions plots show that each solution is close to each

Configuration	Agg. Pref. Score	UW Anchors Depth	BIMS layer Bottom Level	SP-extension Bottom Level	ECI-price [€]	CO2 [kg]	Costs [€]	Pref. ECI	Pref. CO2	Pref. Costs
IMAP Run 2	**100.00**	-	12.31 +m N.A.P	-	1.480	9.425	32.130	99,26	99,68	92,35
BIMS	**95.57**	-	12,00 +m N.A.P	-	3.940	25.135	69.250	96,35	97,47	81,80
IMAP Run 1	**94.13**	-	12,41 +m N.A.P	4,47 +m N.A.P	4.935	37.915	74.525	95,18	95,66	80,67
SP-extension	**93.85**	-	-	4,00 +m N.A.P	6.015	47.235	60.450	93,90	94,35	83,96
UW Anchors	**89.94**	9,50 +m N.A.P	-	-	6.570	71.875	111.005	93,25	90,88	73,96
New sheet pile	**0.00**	-	-	-	85.500	716.500	780.000	0	0	0

Table 4.8: Aggregated Preference Scores for each configuration of quay wall Versteijnen

other, while the costs plot shows that placing UW anchors achieves a lower preferred score than the other alternatives. Finally, the figure also shows again the new sheet pile construction which is the least favourable option for each objective and therefore scores 0 for each objective.



(a) ECI-price stakeholder

(b) CO2 emissions stakeholder

(c) Costs stakeholder

Figure 4.4: Preference curves and applicable solutions for quay wall Versteijnen

4.4.4. Verification of Optimised Adjustments

To verify the preferred configuration of adding BIMS as soil layer with bottom level +m N.A.P 12.00, a PLAXIS model was created that includes this configuration to compare its results with the tool results. Table 4.9 shows the results of both. Again, calculations are included for both the ULS and SLS. As the table shows, the preferred configuration is verified by the PLAXIS model, which shows that each unity check is below 1 and thus no failure mechanism is active any more. In contrast, it is noticeable that the calculated unity checks of the bending moment in the ULS are very different from each other, while in the SLS they are almost equal to each other. However, since they are both below 1, this has no consequences. Moreover, all other calculated values are in line with each other, confirming that the preferred solution is applicable in the models of both methods.

	ULS		SLS	
	Tool (Dsheet)	**PLAXIS**	**Tool (Dsheet)**	**PLAXIS**
Calculated	**Future Situation Adjustments**		**Future Situation Adjustments**	
Max. Moment [kNm/m]	103.66	64.71	40.12	41.19
UC_M	**0.90**	**0.56**	**0.35**	**0.36**
Anchor Force [kN/m]	152.81	132.21	96.27	64.14
UC_A	**0.96**	**0.83**	**0.60**	**0.40**
Shear Force [kN/m]	78.45	84.52	51.98	55.43
UC_V	**0.16**	**0.17**	**0.11**	**0.11**
Displacement [mm]	-	-	18.00	35.94
UC_D	**-**	**-**	**0.34**	**0.68**

Table 4.9: Calculations of future situation with optimised adjustments in both the ULS and SLS of quay wall Versteijnen

5 Discussion

This chapter elaborates on the findings obtained. First, it presents the outcomes of a sensitivity analysis conducted for each case study to gain more insight into the sensitivity of input parameters. Hereafter, it discusses the results per considered adjustment by analysing both the results of chapter 4 and the results of the sensitivity analyses. Lastly, it discusses the validation of the developed tool by considering the conducted needs-analysis, added value, other notable findings and possible improvements of the tool.

5.1. Sensitivity Analysis

To better understand the results and gain more insight into the sensitivity of certain input parameters in the model, a sensitivity analysis can be carried out for each case. This involves varying in both specific sheet pile input parameters and optimisation input parameters. For the sheet pile parameters, the active top loads, soil parameters and corrosion can be varied. One goal here is to explore whether the lifetime of the quay walls could be extended even without adjustments, which remains the ultimate goal from the circular design perspective. Another goal is to identify what adjustments would apply to the sheet piles under varying conditions, for example in case of larger top loads or less favourable corrosion conditions in the future. For the optimisation parameters, the weights of stakeholders can be varied as these can differ per construction project. Here, the goal is to explore whether other optimised results emerge. This section initially explains the approach for each analysis, after which it highlights the results of each analysis per case study:

- **Variation in Top Loads**: Appendix B shows the top loads that are active at each considered quay wall. As these have a significant impact on the resulting soil stresses, reducing these loads could be an effective adjustment as section 2.3 already explained. However, these top loads are often caused by functional requirements such as sand or container storage or the use of a crane. Although it is not always possible to vary the top loads because of these functional requirements, it is interesting to investigate what the impact would be. If reducing is not possible, it is also possible to investigate what happens if the top loads are placed further back. In addition, it is also interesting to see what adjustments would still apply if top loads are increased, which may be the case in the future due to changed functional requirements. As the top load size varies for each sheet pile, the situations of varying the top load differs across the case studies. These will therefore be explained together with the results.

- **Variation in Soil Parameters**: Appendix B shows the soil materials and corresponding soil parameters of each considered quay wall. These soil materials are usually found by conducted cone penetration tests (CPTs), which will most probably not change in the future. However, the corresponding soil parameters are normally determined by using the values of table 2b of the NEN9997 [24] which includes the characteristic values of soil materials, established by lab proofs. If this table is used, a conservative value should be chosen as characteristic value to avoid that a design is created which is based on too favourable parameters. While this makes sense for safety reasons, it can also lead to using values that have been estimated too conservatively. Effect of this could be that a design is created in which adjustments are applied, while if less conservative values were used for certain soil parameters, no adjustments need to be applied at all. Therefore, for this analysis, the effect on each considered quay wall is examined if less conservative soil parameters are used. The condition is that these values were found by performing lab investigations instead of using table 2b from the NEN9997 [24]. The soil parameters that will be improved are the cohesion, c, and friction angle ϕ. As the delta friction angle, δ, is equal to $\frac{2}{3}\phi$, this value will also change with the improvement of ϕ.

- **Variation in Corrosion Rate**: Section 2.1.5 explained that undisturbed, clean soil is assumed for the deterioration of a sheet pile on the land side and for the water side, clean fresh water is assumed. With a target lifetime of 50 years, these assumptions correspond to an deterioration of 0.60mm and 0.90mm in total respectively according to the CUR-166 [8]. In practice, however, tests should be carried out on the sheet pile to determine what effect corrosion has had over the years. This may be more conservative than expected, but also more favourable than expected. In addition, corrosion may also vary over the length of the sheet pile wall because certain sections are more sensitive to corrosion than others. However, as this depends on specific conditions, it is still assumed for this sensitivity analysis that corrosion applies along the entire length of the sheet pile wall. For this analysis, different corrosion rates than those initially used will therefore be used to investigate the consequences.
- **Variation in Weights Stakeholders**: As section 3.4.1 explained, the weights of each stakeholder was set to 0.4 for the ECI-price and CO2 emissions and 0.2 for the costs. However, some results in chapter 4 showed that certain adjustments scored better than the found preferred configuration on individual targets, while the overall aggregated preference score determined different. To investigate if other optimised results will be found if different weights are set and because the weights can differ per case study, this analysis will be conducted by using a weight of 0.1 for both the ECI-price and CO2 emissions and a weight of 0.8 for the total costs.

Each aspect of the sensitivity analysis mentioned above is applied to each case study. To easily refer to the quay walls and corresponding results that chapter 4 highlighted, these will be referenced as the results of the 'baseline cases'.

5.1.1. Quay Wall Van Casteren

- **Variation in Top Loads**: Appendix B includes the three top loads that are active at quay wall Van Casteren, which are:

  1. A line crane load of 160 kPa from 0.00 till 0.80 metres behind the sheet pile
  2. A flat crane load of 25 kPa from 0.00 till 5.00 metres behind the sheet pile
  3. Sand storage of 206 kPa from 5.00 till 40.00 metres behind the sheet pile

  Table 5.1 shows the scenarios that are tested for quay wall Van Casteren and the corresponding results, based on the top loads that are active. For the first scenario the results show that removing the crane loads negatively affects the sheet pile compared to the results of the baseline case as table 4.1 showed, as the sheet pile should be extended by 0.5 m longer. Also, adding BIMS is no longer an option to reinforce the sheet pile scenario. While it was expected that less adjustments would be necessary, it is thus obtained that the sheet pile extension should be 0.5 m longer than the baseline case and BIMS is no longer applicable. This effect can be explained because in Dsheet, the crane load that is active just after the sheet pile has a positive effect on the total stability of the sheet pile. This is as the crane load pushes the top of the wall forward and the active anchor works as a pivot point. This ultimately reduces the overall displacement, resulting in fewer adjustments. However, when this top load is removed, this effect will be reversed and it can be found that increased quantities per adjustment are needed to produce a design that satisfies. So if the crane load is not present, the displacement becomes greater, which requires a longer extension of the sheet pile. Although this effect can be explained, a different result would be found in PLAXIS because of the heavy crane load. The verification of this result for this particular scenario can therefore be questioned. The second scenario shows that the sand storage must be reduced by 23.8% to no longer require sheet pile adjustments. Since this remains the ultimate goal, this shows a very positive result that should be discussed with the user of the quay. For future situations, the scenarios to increase the sand storage are also tested. It is found that if the sand storage would be increased by 25%, the same type of adjustments could be applied as for the baseline case, except for adding BIMS as soil layer. Increasing the sand storage by 50% results in the same adjustments and dimensions as the situation where the sand load was increased by 25%. Thus, if future expansions in the use of the quay are to be considered, it may be more optimal to apply these adjustments and corresponding dimensions in stead of the preferred configuration of extending the sheet pile until bottom level 5.0 +m N.A.P obtained in chapter 4.

Scenario	Results
1. Remove both crane loads	1. Extend sheet pile until bottom level 4.5 +m N.A.P. 2. Place UW anchors on level 9.5 +m N.A.P
2. Reduce sand storage by 23.8 % till 80 kPa	No adjustments are needed for a design that satisfies
3. Increase sand storage by 25% till 131 kPa	1. Extend sheet pile until bottom level 4.5 +m N.A.P. 2. Place UW anchors on level 9.5 +m N.A.P
4. Increase sand storage by 50% till 158 kPa	1. Extend sheet pile until bottom level 4.5 +m N.A.P. 2. Place UW anchors on level 9.5 +m N.A.P

Table 5.1: Scenarios of varying top loads and corresponding results for quay wall Van Casteren

- **Variation in Soil Parameters**: By trial and error it is found that if the soil parameters cohesion c and internal friction angle ϕ of all soil layers are improved by only 3%, no structural adjustments have to be applied to quay wall Van Casteren to be able to withstand the future water bottom level. While this sounds promising, it implies that this improvement must be applied to any soil material because that is how it has been tested. In addition, conducting laboratory tests to demonstrate these improvements does not guarantee success and thus the tests may result in no improvements. Moreover, laboratory tests can be expensive, so these costs should also be taken into account when it is compared to the structural adjustments. Nevertheless, if it can be proven that 3% less conservative values may be used for c and ϕ, no structural adjustments need to be applied resulting in no ECI-price or CO2 emissions at all. So, although there is no guarantee of success, conducting lab tests thus holds much potential, as no adjustments will be necessary if an improvement in parameters is found.

- **Variation in Corrosion Rate**: Table 5.2 shows the scenarios and corresponding results of the varying corrosion rates for quay wall Van Casteren. For the first two scenarios, the corrosion rates that were initially assumed are raised and lowered by a factor 1.5 and 0.5 respectively. However, the results are the same adjustments and dimensions that were found for the baseline case. While this indicates that the corrosion rate has little impact on the model and results, scenario 3 presents a different view. For this scenario, different assumptions that are stated in the CUR-166 [8] are used for the corrosion rate. For the land side, polluted and disturbed soil is assumed which corresponds to a deterioration of 1.50mm over 50 years, which is 2.5 times as large as the initially assumed 0.60mm. For the water side, highly polluted fresh water is assumed which corresponds to a deterioration of 2.30mm over 50 years, which is also approximately 2.5 times as large as the initially assumed 0.90mm. Using these rates, it is found that no adjustments could be applied to create a design that is satisfactory. However, since the total deterioration is equal to 3.80 mm and an AZ-13 sheet pile section is used for quay wall Van Casteren which has an initial thickness of 9.5 mm, that means there will be 40% decrease in thickness in 50 years. Since Quay Van Casteren has also already been in use for 21 years, a 17% decrease must be added to that. This means that less than half of the original thickness is left, if reinforced for 50 years under these assumptions. From that point of view, a sheet pile wall can be difficult to reinforce and renewal remains an only option. It is therefore important to carry out accurate corrosion measurements on a sheet pile wall to determine whether and what adjustments may be applicable.

- **Variation in Weights Stakeholders**: Table 5.3 shows the optimised result of the tool if the set weights for the stakeholders are changed for quay wall Van Casteren. As the table shows, no different result is obtained. This could have been expected as table 4.2 shows that extending the

Scenario	Results
1. Raise corrosion rates by factor 1.5: Landside: 0.90 mm Waterside: 1.35 mm	1. Extend sheet pile until bottom level 5.0 +m N.A.P 2. Add BIMS layer with bottom level 11.0 +m N.A.P 3. Place UW anchors on level 9.5 +m N.A.P
2. Lower corrosion rates by factor 0.5: Landside: 0.30 mm Waterside: 0.45 mm	1. Extend sheet pile until bottom level 5.0 +m N.A.P 2. Add BIMS layer with bottom level 11.0 +m N.A.P 3. Place UW anchors on level 9.5 +m N.A.P
3. Different assumption are used for corrosion: Polluted soil, disturbed soil. Landside: 1.50 mm Highly polluted fresh water. Waterside: 2.30 mm	No applicable adjustments were found

Table 5.2: Scenarios of varying corrosion rates and corresponding results for quay wall Van Casteren

sheet pile has the highest preference score for both the ECI-price, CO2 emissions and total costs compared to the other applicable configurations for quay wall Van Casteren.

Optimised Result	$\mathbf{W}_{ECI}$	$\mathbf{W}_{CO2}$	$\mathbf{W}_{Costs}$	**ECI-price** [€]	**CO2** [kg]	**Costs** [€]
Extending s.p until bottom level 5.16 +m N.A.P	0.4	0.4	0.2	1.180	9.780	35.540
Extending s.p until bottom level 5.16 +m N.A.P	0.1	0.1	0.8	1.180	9.780	35.540

Table 5.3: Optimised results of different stakeholder weights for quay wall Van Casteren

5.1.2. Quay Wall 28

- **Variation in Top Loads**: Appendix B includes the two top loads that are active at quay wall 28, which are:

  1. A crane load of 350 kPa from 0.50 till 1.35 metres behind the sheet pile
  2. A crane load of 77 kPa from 6.50 till 7.25 metres behind the sheet pile

  Table 5.4 shows the varying top loads scenarios and the corresponding results for quay wall 28. Since a top load of 350 kPa is already used in the current situation, no situation is created in which the top loads are increased. For the first scenario, where both crane loads are removed, the table shows that no adjustments are needed to create a design that satisfies. The same result holds for the third scenario, in which both crane loads are placed 4.5 metres back, so that no loads are active on the first 5 metres behind the sheet pile. Although completely removing the crane loads might not be a realistic solution due to the functional requirements of the quay wall, moving the crane loads further back could be discussed with the quay user as a potential solution. If it turns out to be an option, it has great potential as it would result in an ECI-price of 0, no CO2 emissions and no costs to be able to withstand the future deepening. If the loads are only moved 2 metres back, which is scenario 2, it turns out that adjustments should still be applied. Whereas adding BIMS and placing UW anchors with the same dimensions were also applicable adjustments for the baseline case of quay wall 28, it turns out that extending the sheet pile by 0.5 m until 4.81 +m N.A.P and placing colloidal concrete of 0.5 m thick are also applicable adjustments when the crane loads are moved to the back. Therefore, if turns out that moving the crane loads is an option for the user of the quay, scenario 3 is more favourable than scenario 2 as no adjustments would be necessary at all.

- **Variation in Soil Parameters**: By trial and error it is found that if the soil parameters cohesion c and internal friction angle ϕ of all soil layers are improved by only 6%, no structural adjustments have to be applied to quay wall 28 to be able to withstand the future water bottom level. As discussed in section 5.1.1, this improvement has to be applied to every soil layer present and cannot be guaranteed by performing laboratory tests. Still, just as for quay wall Van Casteren, it contains great potential because no adjustments would be needed at all.

- **Variation in Corrosion Rate**: Table 5.5 contains the possible scenarios when varying in corrosion rates and the corresponding results of quay wall 28. For the first scenario, raising the initial

Scenario	Results
1. Remove both crane loads	No adjustments are needed for a design that satisfies
2. Place both crane loads by 2 metres back	1. Extend sheet pile until bottom level 4.81 +m N.A.P 2. Add BIMS layer with bottom level 10.50 +m N.A.P 3. Place UW anchors on level 9.5 +m N.A.P 4. Place colloidal concrete of 0.5 m thick
3. Place both crane loads by 4.5 metres back	No adjustments are needed for a design that satisfies

Table 5.4: Scenarios of varying top loads and corresponding results for quay wall 28

corrosion rates by a factor 1.5, it is found that placing anchors above and under the waterline with the same dimensions as for the baseline case can be used as structural adjustments. However, adding BIMS is no longer an option in comparison with the results of table 4.5. For scenario 2, lowering the corrosion rates by a factor 0.5, it holds that the same adjustments and dimensions as the baseline case can be used, while extending the sheet pile by 2 metres until bottom level 3.31 +m N.A.P is an option now as well. For the last scenario, using different assumptions for the corrosion rates, it is found again that no adjustments can be applied to create a design that satisfies. Since quay wall 28 uses a BZ-IV-N sheet pile profile with an initial thickness of 14 mm and has been in use for 15 years, a total thickness reduction of about 35% should hold for the additional 50 years. Apparently, the adjustments considered are not able to withstand this. Based on this result, it is therefore found again that it is important to carry out accurate corrosion measurements on a sheet pile structure to determine if adjustments may be applicable.

Scenario	Results
1. Raise corrosion rates by factor 1.5: Landside: 0.90 mm Waterside: 1.35 mm	1. Place AW anchors of 14.0m 2. Place UW anchors on level 9.5 +m N.A.P
2. Lower corrosion rates by factor 0.5: Landside: 0.30 mm Waterside: 0.45 mm	1. Place AW anchors of 14.0m 2. Place UW anchors on level 9.5 +m N.A.P 3. Add BIMS layer with bottom level 10.50 +m N.A.P 4. Extend sheet pile until bottom level 3.31 +m N.A.P
3. Different assumption are used for corrosion: Polluted soil, disturbed soil. Landside: 1.50 mm Highly polluted fresh water. Waterside: 2.30 mm	No applicable adjustments were found

Table 5.5: Scenarios of varying corrosion rates and corresponding results for quay wall 28

- **Variation in Weights Stakeholders**: Table 5.6 shows the optimised result of the tool if the set weights for the stakeholders are changed for quay wall 28. As the table shows, no different result is obtained than the baseline case and therefore, according to the tool, the optimised result remains to place AW anchors of 12 metres long. Table 4.5 shows that the results obtained by the GA have the highest preference score for both the ECI-price and total costs compared to the other applicable configurations for quay wall 28. As the cost weight was increased from 0.2 to 0.8, AW anchors could be expected to remain the preferred configuration because adding BIMS is about 2 times more expensive than the anchors.

Optimised Result	$\mathbf{W}_{ECI}$	$\mathbf{W}_{CO2}$	$\mathbf{W}_{Costs}$	**ECI-price** [€]	**CO2** [kg]	**Costs** [€]
Placing AW anchors of 12.00m	0.4	0.4	0.2	12.815	140.245	108.300
Placing AW anchors of 12.00m	0.1	0.1	0.8	12.815	140.245	108.300

Table 5.6: Optimised results of different stakeholder weights for quay wall 28

5.1.3. Quay Wall Versteijnen

- **Variation in Top Loads**: Appendix B includes the two top loads that are active at quay wall Versteijnen, which are:

1. A uniform load of 20 kPa from 0.00 till 3.00 metres behind the sheet pile
2. A container load of 45 kPa (3 layers) from 3.00 till 25.00 metres behind the sheet pile

Table 5.7 shows the varying top loads scenarios and the corresponding results for quay wall Versteijnen. For the first scenario, removing the uniform load on the first 3 metres behind the sheet pile, it is found that the same adjustments and dimensions as for the baseline case holds that table 4.8 showed. At quay wall Versteijnen, a container load of 45 kPa is active which is equal to 3 layers of containers. For scenario 2, these are reduced till 2 layers of containers resulting in a top load of 35 kPa. For this scenario, it is found that no adjustments are needed for a design that satisfies. This is a finding with a lot of potential that can also be called remarkable, as quay wall Versteijnen has been in operation since 1966. For scenario 3, the containers are increased by an extra layer resulting in a top load of 55 kPa. For this scenario, it is found that adding BIMS and placing UW anchors are adjustments that can be applied. So, from a future point of view, these would be adjustments that could be properly applied so that the top loads could even be increased in the future.

Scenario	Results
1. Remove uniform load	1. Extend sheet pile until bottom level 4.00 +m N.A.P 2. Add BIMS layer with bottom level 12.00 +m N.A.P 3. Place UW anchor on level 9.50 +m N.A.P
2. Reduce container load till 35 kPa (2 layers)	No adjustments are needed for a design that satisfies
3. Increase container load till 55 kPa (4 layers)	1. Add BIMS layer with bottom level 11.00 +m N.A.P 2. Place UW anchor on level 9.50 +m N.A.P

Table 5.7: Scenarios of varying top loads and corresponding results for quay wall Versteijnen

- **Variation in Soil Parameters**: By trial and error it is found that if the soil parameters cohesion c and internal friction angle ϕ of all soil layers are improved by only 3%, no structural adjustments have to be applied to quay wall Versteijnen to be able to withstand the future water bottom level. Again, this improvement has to be applied to every soil layer present and cannot be guaranteed by performing laboratory tests. Still, just as for quay wall Van Casteren and for quay wall 28, it contains great potential because no adjustments would be needed at all.

- **Variation in Corrosion Rate**: Table 5.8 shows the varying corrosion rate scenarios and corresponding results of quay wall Versteijnen. As quay wall Versteijnen is already in use since 1966, it has spent 57 years. As a result, the current deterioration is already 1.71 mm when assuming the initial corrosion rates. Since quay wall Versteijnen makes use of a BZ-I-N profile with an original thickness of 8 mm, it currently has thus a thickness of 6.29 mm. It is therefore interesting to obtain the results when different corrosion rates are used. For the first scenario, raising the initial corrosion rates by factor 1.5, it is found that adding BIMS and placing UW anchors are still applicable adjustments. However, for the BIMS layer, the bottom level should now be on 10.50 +m N.A.P instead of 12.00. For the second scenario, lowering the corrosion rates by factor 0.5, the same adjustments can be applied as for the baseline case which table 4.8 showed. For extension of the sheet pile however, it is even improved that the sheet pile should only be extended by 0.5 m until 5.00 +m N.A.P instead of 4.00 +m N.A.P. For the other two adjustments, the same dimensions hold. For the third scenario, in which different assumptions are used for the corrosion rates, it is found again that no adjustments can be applied to create a design that satisfies. Which was to be expected, as these corrosion rates would mean a deterioration of 3.80 mm on top of the current thickness of 6.29 mm. This would leave a thickness of about 2.50 mm, which is only about 1/3 of the original thickness.

- **Variation in Weights Stakeholders**: Table 5.9 shows the optimised result of the tool if the set weights for the stakeholders are changed for quay wall 28. As the table shows, no different result is obtained than the baseline case and therefore, according to the tool, the optimised result remains adding BIMS as soil layer with bottom level 12.31 +m N.A.P. This could have been

Scenario	Results
1. Raise corrosion rates by factor 1.5: Landside: 0.90 mm Waterside: 1.35 mm	1. Add BIMS layer with bottom level 10.50 +m N.A.P 2. Place UW anchors on level 9.5 +m N.A.P
2. Lower corrosion rates by factor 0.5: Landside: 0.30 mm Waterside: 0.45 mm	1. Add BIMS layer with bottom level 12.00 +m N.A.P 2. Place UW anchors on level 9.5 +m N.A.P 3. Extend sheet pile until bottom level 5.00 +m N.A.P
3. Different assumption are used for corrosion: Polluted soil, disturbed soil. Landside: 1.50 mm Highly polluted fresh water. Waterside: 2.30 mm	No applicable adjustments were found

Table 5.8: Scenarios of varying corrosion rates and corresponding results for quay wall Versteijnen

expected as table 4.8 shows that adding BIMS has the highest preference score for both the ECI-price, CO2 emissions and total costs compared to the other applicable configurations for quay wall Versteijnen.

Optimised Result	W_{ECI}	W_{CO2}	W_{Costs}	**ECI-price** [€]	**CO2** [kg]	**Costs** [€]
Add BIMS layer with bottom level 12.31 +m N.A.P	0.4	0.4	0.2	1.480	9.430	32.130
Add BIMS layer with bottom level 12.31 +m N.A.P	0.8	0.1	0.8	1.480	9.430	32.130

Table 5.9: Optimised results of different stakeholder weights for quay wall Versteijnen

5.2. Interpretation of Results

For each case study a different preferred configuration is determined. In addition, the sensitivity analysis of each case study provided results for further analysis. This section therefore elaborates on both the baseline case results and the sensitivity analysis results for each type of structural adjustment, to increase insight in the potential of each adjustment.

5.2.1. Replacing a soil layer for lightweight material

Using BIMS as soil layer at the active side of the quay wall is found as applicable structural adjustment for each case. For quay wall Van Casteren, table 4.2 shows that the use of BIMS has an aggregated preference score of 86.54, which is about 13% lower than the score of 99.37 for the preferred configuration which included extending the sheet pile. This is mainly because BIMS scored about 30% lower on the cost preference score, namely 62.53 compared to the 88.41 of the sheet pile extension. While this might suggest that BIMS is much more expensive in material terms, this is due to the quantities required for both adjustments. This is because the sheet pile only needs to be extended by 0.5 metres, while the BIMS layer needs to be 1.5 metres thick.

The results of quay wall 28 include the same finding, as table 4.5 shows that using BIMS has a preferred score of 49.70 on costs, while the preferred configuration of placing AW anchors scored 70.28 on this objective. As a result, BIMS has an aggregated preference score of 94.75, which is about 1% lower than placing the AW anchors with a score of 96.14.

However, for quay wall Versteijnen, adding BIMS is determined as the preferred configuration. For that case it was found that a BIMS layer should be added with a bottom level of 12.00 +m N.A.P and thus a thickness of 0.5 m. Since only a layer of 0.5 m thick should be used, it has a preference score of 81.80 for the costs, resulting in an aggregated preference score of 95.57.

The sensitivity analyses provide additional insights. For quay wall Van Casteren, it is found that the adjustment is applicable when corrosion rates are increased, but it becomes inapplicable if the top loads are increased. The sensitivity analysis of quay wall 28 also shows that increasing the corrosion rates results in that BIMS is no longer applicable as structural adjustment. However, for quay wall Versteijnen, it appears that if the corrosion rates and top loads are increased the use of BIMS is still applicable.

In conclusion, since the baseline case results of each case show that BIMS is an applicable adjustment and the sensitivity analysis of Versteijnen also show that it can be used from a future perspective, it is found that the use of BIMS has great potential as a structural adjustment.

5.2.2. Lowering the pile tip level of a sheet pile

For quay wall Van Casteren, it was obtained that the preferred configuration would be to extend the sheet pile by 0.5 m until bottom level 5.00 +m N.A.P. Also in the sensitivity analysis of this case, it was found that when corrosion or top loads have increased, extending the sheet pile by 0.5 metres is still applicable. This implies that for sheet pile Van Casteren it is best to choose the sheet pile extension as configuration, also from a future perspective. Furthermore, this adjustment was also applicable for quay wall Versteijnen but since it should be extended by 1.5 m for that case it was not found to be the preferred configuration. In the sensitivity analysis of this case, extending the sheet pile was no longer obtained as a possible structural adjustment when the top load and corrosion were increased. However, this could have been expected, since for the baseline case it was already found that extension by 1.5 metres was required. Since quay wall Versteijnen has also been in use since 1966, it will be more difficult to extend it by another 50 years.

For both quay walls the obtained failure mechanism was the soil failure, indicating that the sheet pile wall was unstable. From this finding, it could have been expected that sheet pile extension is one of the applicable adjustments for both quay walls to improve the stability of the wall and is thus proven. However, as extending a sheet pile involves a couple of side activities, it can be argued whether it can be applied in practice as many uncertainties are part of it. After consultation of experts at BAM it is found that extending a sheet pile could be applied under two conditions:

1. The corrosion that has affected the sheet pile should allow it. This means that measurements are taken at the quay walls to measure the effects of corrosion over the past few years and that these effects don't have negatively effected the sheet pile profiles too much. This is because if the thickness would already have decreased too much, the sheet pile cannot be driven down.
2. The locks between the sheet pile profiles must be aligned in such a way that extra sheet pile material can be precisely welded onto them. Also here it holds that corrosion should not have effected the locks too much.

Both quay wall Van Casteren and quay wall Versteijnen should therefore be subject to both conditions if this adjustment is applied. Here, for quay Versteijnen, greater risks can be expected than for quay Van Casteren, due to the fact that quay Versteijnen has been in use for 57 years.

5.2.3. Placing colloidal concrete

Colloidal concrete was considered as material to be added as soil layer at the passive side. This adjustment was not found to be an applicable adjustment at any of the quay walls considered. Only in the sensitivity analysis at quay wall 28 it was found that if the top load was placed further back it would be an applicable adjustment. The theory of this adjustment is that it could provide extra support to the quay wall as an improvement in the soil profile at the passive side. However, the layer that is applied may not exceed the future water bottom level. As a result, it therefore appears that this adjustment can have too little impact on a sheet pile when it is used in this way.

5.2.4. Placing anchors above water

Currently, placing additional anchors above the waterline is the most common adjustment to strengthen a quay wall. However, only at quay wall 28 it was determined that this adjustment could be applied. This is due to the fact that only for this case the failure of the existing anchors was observed in the future situation. Moreover, there was no case study in which no anchors were used, so it was not possible to consider such a scenario. Therefore, if a case study has no existing anchors, it is possible that above water anchors could be used.

For quay wall 28, it was established that placing AW anchors of 14 metres long is the preferred configuration. The sensitivity analysis of this case also found that even when corrosion rates are increased, placing AW anchors is still applicable to reinforce the quay. For the top loads, it was found that if the crane loads are placed 2 metres back it is no longer an option. This can be related due to the fact that the active failure mechanism is no longer the failure of the anchors but the failure of soil resulting in an unstable sheet pile. So based on these results it can be indicated that whenever the unity checks of existing anchors are above or equal to 1, adding anchors above the water line can be used as adjustment in order to relieve the existing anchors. After consultation of experts at BAM, it is found again that two conditions hold before the anchors could be applied in practice:

1. Sufficient space should be available between the existing anchors lengthwise. This means that the centre-to-centre distance between the existing anchors is such that anchors can be placed between them. As this distance is different for each quay, no specific minimum distance can be named.
2. The impact on the existing anchors should be investigated, and only if it is found that there is a positive effect on them the new anchors can be installed. This is due to the fact that the new anchors are placed under a certain pre-tension. This pre-tension can lead to an undesirable result on the existing anchors. If the outcome proves to be positive, there is no cause for concern, and the placement of the new anchors can proceed accordingly.

In the tool, the length of AW anchors is set to be the varying parameter. However, other aspects such as the anchor's angle with the horizontal can also be varied. For this project the angle of the anchor was set at 30 degrees to ensure that the vertical force component of the anchor would not exceed the vertical bearing capacity of the sheet pile. Because an angle of 30 degrees was chosen, the length of the anchor is longer than if a an angle of 45 degrees was used. As a result, if the AW anchors prove to be the preferred configuration while the length is longer than at 45 degrees, it is sufficient at the preliminary design stage to keep it that way. Only if turns out that an anchor of 45 degrees is the preferred configuration and an anchor of 30 degrees is not, it would make sense to change the angle of the anchor.

Besides, the point of engagement of the anchors could also be varied. However, since the placement of underwater anchors is also considered as structural adjustment, it was chosen to keep the above water anchors at 0.5 metres above the waterline.

5.2.5. Placing underwater anchors

As mentioned earlier, the use of UW anchors is currently not common yet and research is taking place to bring them into practice. Therefore, this adjustment has been included in this project from a structural perspective to demonstrate their potential. For each case, it was found that placing UW anchors could result in a design that satisfies when the water bottom was lowered. Furthermore, the sensitivity analyses indicated that placing UW anchors can be applied even if corrosion rates or top loads are increased in possible future use of the quay wall. Thus, both the baseline case results and the sensitivity analyses indicate that the use of UW anchors holds great potential.

Although UW anchors have shown great potential, they are not determined as the preferred configuration for any of the case studies. This is due to the fact that they are relatively expensive, given the individual preference scores that table 4.2 and table 4.8 showed for the costs. However, it should be noted here that these cost assessments are based on an assumption that UW anchors are twice as expensive as AW anchors. In practice this factor may be different, with it more likely to be higher than lower due to the many uncertainties and risks during the placement process. In addition, for the ECI-price and CO2 emissions, it has now been assumed that the same data from AW anchors could be used, but a thorough analysis of this is currently lacking as well. Nevertheless, from both a future-oriented and structural perspective, the results of the tool show that the use of UW anchors holds great potential.

5.3. Validation

This section elaborates on the validation of the developed tool to determine whether the right tool has been created, to identify any missing aspects and to explore potential improvements. The validation is conducted from the perspective of the end user of the tool, which in this case is construction company BAM. The content of this section is therefore based on conversations with BAM employees interested in using the tool. First, the section discusses the needs-analysis that section 3.2 highlighted. Following this, it discusses the added value of the tool and what it specifically enables. Finally, it concludes by evaluating the suitability of the optimisation method of Preferendus in this domain, discussing the generality of the tool and highlighting several potential improvements to the tool.

5.3.1. Needs-Analysis

The section below discusses each technical requirement that section 3.2 included in the conducted needs-analysis. It explains whether a particular requirement has been met or whether certain aspects can still be improved.

- **Automated tool, dependent only on input data**: This requirement has been met. The input data that should be entered are sheet pile specifics, geometric specifications, active top loads, use of anchor and if so, the anchor specifics and lastly the soil profiles, including soil materials and corresponding parameters. Besides this structural input, the GA and Preferendus settings should be inserted. After the input data is insert, the tool automatically calculates the current situation and future situation in which the water bottom level is deepened. If failure mechanisms are active, the structural adjustments that section 3.3 mentioned are tested automatically. Eventually the preferred configuration of structural adjustments will be the output.
- **Applicable on each existing steel sheet pile**: This requirement has been met. Meaning that each steel sheet pile that can be set in Dsheet, can be set in the tool. As a result, each quay wall segment can be calculated more efficiently. In addition, the tool provides insight into the possible bundling of solutions of different quay segments.
- **Tested for failure mechanisms, both without and with adjustments**: This requirement has been met. However, it should be noted that only the most critical failure mechanisms of a sheet pile wall are included in the tool, as section 2.1.3 already explained. It is therefore assumed that if the tool does not identify any failure mechanisms, then no other, more specific failure mechanisms are active, given that the evaluated mechanisms are the most critical. Moreover, the failure mechanisms determined by the tool come from a Dsheet analysis, while chapter 4 found that differences in failure mechanisms could occur when a case is calculated by PLAXIS. However, as for each case the preferred configuration resulted in a satisfactory design in both Dsheet and PLAXIS, these differences were not found to be essential.
- ***A-priori* design optimisation of structural adjustments**: This requirement has been met. Due to the application of the Preferendus an *a-priori* design optimisation method is used. This enables to directly determine the preferred configuration of structural adjustments. As a result, a configuration is obtained that contains the maximum aggregated preference score of all stakeholders while satisfying the systems constraints. In addition, insight is gained in the costs, ECI-price and CO2 emissions of each adjustment as well.

5.3.2. Added Value of Tool

In addition to the technical requirements met by the developed tool, the tool fills a number of development gaps that currently exist. The added value of the tool is therefore emphasized by comparing the use of the tool with the situation where the tool is absent. This is addressed by highlighting the three main advantages of the developed tool:

1. **Increased efficiency**: A variants study of structural adjustments for an existing sheet pile is currently being carried out during the preliminary design phase of a design process. Through trail & error and manual calculations, all the different adjustments and associated varying dimensions are tested. Due to the many iterations involved in this process, a lot of time is spent on these calculations. However, the calculation process is exactly the same for each iteration and this process could therefore be automated. The developed tool enabled it to automate this process through a Python script that integrates with Dsheet for the sheet pile calculations. In this script, all considered adjustments are inserted together with the varying dimensions.

Besides testing all individual adjustments, the tool also allows combinations of adjustments to be calculated during the optimisation stage. Without the tool, this takes extra calculation time, as at least two adjustments are considered whose dimensions are varied for both. Because of the developed script, a user of the tool only needs to enter the input parameters of a particular sheet pile and run the script. The tool then calculates the sheet pile in both the current and future situation, analyses whether certain failure mechanisms will occur and tests each adjustment by performing a calculation for each varying parameter. As a result, the tool's user saves a lot of time since they no longer need to perform the repetitive calculations themselves.

Furthermore, the repetitive process described above is relevant to every individual segment of a quay wall. For instance, the quay wall of the case studies in Tilburg comprises 32 distinct segments. Utilising the tool significantly saves time, as it eliminates the need for manually conducting a variant study for each segment. The user can then use this time for in-depth analyses requiring engineering expertise instead of performing long and repetitive calculations.

Due to this increased efficiency, the tool also enables a sensitivity analysis to be carried out easily. In this sensitivity analysis, future situations can be entered, such as an increase in top load or changing corrosion conditions. While this would have required considerable additional calculation time without the tool, it can now be easily executed by it. The same applies to specific sheet pile information that becomes increasingly available during the preliminary design phase. While initial calculations are often performed with assumptions for missing input data, they can now be revised more efficiently by the tool if more accurate information becomes available. As a result, the tool also enables it to obtain a more accurate status of a considered sheet pile wall.

2. **Financial and environmental impact insights**: Besides making a variants study more efficient, the tool enabled it to show the financial and environmental impact of all adjustments and combine this with the sheet pile calculations. As a result, this not only provides insight into whether a feasible design of a sheet pile has been created but immediately reveals what the associated ECI-price, CO2 emissions and costs are as well. Currently, these effects are calculated only after the completion of the variants study, with the same calculations being made again for each parameter that varies.

   Moreover, these effects are calculated by a different team of financial or sustainability experts. However, it would be much more efficient to perform these at the same time as the sheet pile calculations and by the same people who perform these sheet pile calculations. Therefore, the tool has enabled this, again saving a lot of time as manual calculations no longer need to be performed and no other team of experts have to be consulted during the preliminary design phase. As a positive consequence, this also eliminates potential calculation errors in the financial and sustainability calculations.

3. **Direct determination of preferred solution**: Besides making a variants study more efficient and providing insight into the environmental and financial impacts of all adjustments, the tool enabled it to directly determine the preferred configuration of structural adjustments. Currently, the preferred solution is determined by analysing a number of variants and collectively evaluating their financial and environmental impacts with all involved stakeholders. This process leads to a subjective, *a-posteriori* determination of the preferred solution, often requiring stakeholders to compromise on their objectives, potentially delaying the consensus on an preferred outcome.

   The tool has therefore enabled it to directly determine this preferred configuration of structural adjustments. By applying the Preferendus, which uses an *a-priori* design optimisation method, it has become possible to directly determine the configuration that contains the maximum aggregated preference score while satisfying the technical constraints of the system. The tool is able to maximise on preference score as the stakeholders' preferences and the weight per stakeholder are defined before the optimisation process. Besides, the technical constraint to create a design that satisfies could be incorporated as well, as the Preferendus enables to include the desirability's of involved stakeholders and the capabilities of a certain object. The configuration that eventually is determined by the tool could be a combination of adjustments, but the tool could also determine that this is only one type of adjustment. By also including the combination of adjustments, the tool enabled it to determine the actual preference, compared to if the structural adjustments had only been tested individually.

5.3.3. Application of the Optimisation Method of Preferendus

Whereas the development of the tool enabled many possibilities, some aspects could be questioned as well. For example, based on the obtained results, it can be argued whether applying the optimisation method of Preferendus to find the preferred configuration is the best method. Although the idea of applying it was to find the preferred configuration of adjustments, which could be a combination of adjustments, it turned out that only one type of adjustment was the preferred configuration for each case study. This is due to the fact that there were no conflicting objectives, as both financial and environmental impacts had to be minimised. This minimisation approach looks for the minimum required amount of a combination of adjustments or one type of adjustment to achieve a design that satisfies. To determine if combining adjustments results in lower ECI-price, CO2 emissions, and costs, slack has been given to the minimum required amount of each individual adjustment. This approach enables that the combination of adjustments can be determined as preferred configuration. Still it turned out that the preferred configuration for each case was only one type of adjustment.

The discussion is therefore raised if the output of the tools weighs up against the computational time of the model. As section 3.4.2 already mentioned, the computational time of the model could rise up to 3 hours because of the many iterations and Dsheet calculations that are performed. While 3 hours in itself is still manageable, the question is whether these 3 hours are wasted considering that these individual adjustments could have been found without applying the Preferendus as well. However, if the Preferendus had not been used and thus the combinations of adjustments were not tested, it cannot be verified whether the preferred configuration was found because the combinations were not tested at all. Moreover, it could be that if other quay walls had been considered, the preferred configuration could have been a combination of adjustments. In addition, the application of Preferendus did make it possible to directly determine the preferred configuration resulting in a maximised aggregated preference score. Applying the optimisation method of Preferendus within this project therefore clearly demonstrates added value.

5.3.4. Generic tool

The developed tool is intended as a generic tool that can be applied to any sheet pile wall during the preliminary design phase. This assumes that the considered adjustments can always be applied. In practice, however, it varies per case whether certain adjustments can be applied. This depends among others on environmental conditions that could lead to potential construction hindrance. For example, there may be physical obstacles present on land behind the sheet pile, such as a 100-year-old tree or an old factory that may not be moved or removed due to missing permits. In addition, the waterway next to the sheet pile may not be closed for construction activities due to possible waterway obstruction that could occur. Moreover, specific site conditions such as the accessibility of materials could lead to potential construction hindrance as well. To include these specific situations in making the preferred decision, construction hindrance on land and construction hindrance on water have been defined in the tool. The user of the tool can indicate for both these situations whether they take place. If so, certain adjustments will not be included in the variant study carried out. If there is construction hindrance on land, adding a BIMS layer is no longer possible, as this requires adjustments to the ground layers on the active side. If there is construction hindrance on water, the placement of colloidal concrete is not evaluated, as the correct placement of this adjustment can only be done from the water. Placing anchors, both above and underwater, and extending the sheet pile, can be done from both land and water, so nothing changes for these adjustments. Based on these user-defined settings, the preferred configuration is searched from the adjustments that were not initially dropped.

As this is only a starting point for how construction hindrance can be implemented in the tool, it could be further improved during future use of the tool. This is justified, as the tool is currently developed to serve as a generic tool and to serve as a decision support tool rather than a tool to deliver a final design. Implementing the construction hindrance this way therefore only further improves the tool’s usability while the actual implementation of certain adjustments will always have to be determined by a team of structural engineers. In short, the tool can provide a lot of insight and knowledge into the options for strengthening an existing quay wall, but it will not be able to determine a final design, as it is not designed to do so.

The point about using a generic tool also applies to the data used for the ECI-price, CO2 emissions and costs per adjustment. The same generic values are now used for each case, in stead of that these values are determined based on specific sheet pile conditions. However, during the preliminary design phase the aim is to discover what might be possible to reinforce the quay and what the theoretically most preferred solution would be. By using generic values, it has become possible to obtain this theoretical preference in a quick and simple way. Therefore, the use of generic values is justified. It is therefore important however, that if the results are used for a final design, the ECI-price, CO2 emissions and costs are again critically reviewed by experts.

5.3.5. Improvements of tool

Although the tool enabled many features and currently contains all technical requirements, the application of the tool can be further improved by implementing the improvements listed below:

- **Include more structural adjustments**: The developed tool enables automatic testing of structural adjustments to an existing sheet pile wall. However, not all theoretically possible adjustments to strengthen a sheet pile that section 2.3 highlighted are included in the developed tool. This is due to the integration with Dsheet, in which several adjustments cannot be inserted. Also, some of these adjustments are not expected to have great potential. These expectations are however based on engineering judgement and not on a thorough structural analysis. However, it should be noted that some of the included adjustments are examples of possibilities that could be implemented. For example, adding BIMS as a soil layer serves as a way to reduce active soil pressure. The tool currently uses BIMS, but this could also be changed for example to another lightweight fill material such as EPS. The same applies to adding stability to the sheet pile wall, which is now included as adding grout anchors above or below the waterline. However, other types of anchors could have been used and tested. Finally, this applies to increasing passive soil pressure as well, which is now included and tested by placing colloidal concrete. For that adjustment other materials could be tested as well, as long as they have the potential to increase the passive soil stress. Only for extending the sheet pile wall, no other materials or aspects could be tested. Nevertheless, the tool could be improved by implementing more structural adjustments.
- **Include more forces acting on quay walls**: The functionalities of the tool can also be extended by implementing more forces that are acting on sheet piles. For example, the forces that are acting on the bitts on top of the capping beams are currently not included. The same applies to the collision loads caused by ships as they approach the sheet pile wall. Currently, these forces are excluded from the scope, but if they are included, they can offer a more accurate evaluation of possible reinforcement adjustments.
- **Include capping beam and rebar calculations**: Calculations on the feasibility of a capping beam (including rebar) are also currently lacking. These have been left out of scope because the biggest aspect to be investigated by the tool is simply whether the design of the sheet pile would satisfy. Thus, as it was not crucial to include calculations on the capping beam (including rebar), they were neglected. However, including those would improve the accuracy of the tool as well.
- **Determination of possible excavation level**: In addition, the tool currently uses the future excavation level as an input parameter. However, an other improvement for the tool could be to determine the potential excavation level itself. This could be useful in two ways: First, it would then be possible to calculate the possible excavation level for which the sheet pile does not need to use adjustments under the current conditions. This would provide insight into which excavation level could be implemented. Secondly, after determining the preferred configuration of adjustments, it would be possible to determine the maximum level of excavation that could be deepened. This can help provide better insight into future situations where further deepening may be required.

  Currently, this functionality is not included because this tool was originally developed for use in the Rhombus UPSIDE project, which has already determined the type of ships that should be able to enter the involved ports. Because of these ships, the required level of the water bottom has been fixed and therefore the retaining height that the sheet pile wall has to withstand is determined as well. Thus, as it was not necessary for this project, more insight could be provided if the level of the water bottom could be determined by the tool instead of setting it as an input parameter.

- **Include implementation risks**: Finally, the tool could be improved by including implementation risks for each adjustment. Since risks are formulated as the product of probability and consequence, the final consequences can be expressed as costs. In this way, the risks can be converted into costs and included in the total costs of each adjustment. Currently, these risks have been excluded, as only direct costs have been considered. This has been done because the aim of this developed tool is to gain insight into the possibilities of strengthening a particular quay wall rather than providing a final design. It could therefore be that when these risks are considered, a different choice will be made as to which adjustments are chosen for the final design than the preferred configuration determined by the tool.

6 Conclusion and Recommendations

This chapter highlights the conclusions of this thesis first, by considering both the conclusions of the applied structural adjustments and the conclusions of the development of the tool. Finally, it proposes recommendations for follow-up research.

6.1. Conclusions

The conclusions this thesis presents are twofold. The first set of conclusions relates to the applied structural adjustments, derived from the results of the case studies and the conducted sensitivity analyses. The second set evaluates the development of the tool, examining the initial development statement and highlighting the added value of the tool.

6.1.1. Conclusions of structural adjustments

This section presents the conclusions of each structural adjustment applied in this project, evaluating the three options considered to strengthen a quay wall and thus extend its lifetime:

- Lower the active soil pressure:
  - **Replacing a soil layer for lightweight material**: In this project, BIMS served as the chosen lightweight material. The results showed that this adjustment leads to a satisfactory design for each case study, despite the fact that two different failure mechanisms were obtained for these cases. Moreover, it proved to be an applicable adjustment for the future scenarios of the sensitivity analysis of one of the case studies. This means that it can also be applied if, in future situations, the top load of a sheet pile needs to be increased or if a sheet pile is affected more heavily by corrosion than expected. Based on these findings, it can be concluded that replacing a soil layer for BIMS has great potential as a structural adjustment because it is not related to a specific failure mechanism and is also applicable in possible future situations for some cases.
- Increase the passive soil pressure:
  - **Lowering the pile tip level of a sheet pile**: The results showed that this adjustment leads to a satisfactory design for two out of three case studies. In both cases, soil failure was the active failure mechanism, leading to an unstable sheet pile. The sensitivity analysis of these cases showed that this adjustment was applicable in future situations for only one of them. Based on these findings, it can be thus be concluded that this adjustment can mainly be used if the failure mechanism of a sheet pile is the failure of soil which eventually leads to an unstable sheet pile wall.
  - **Placing colloidal concrete**: In this project, colloidal concrete served as material to be added as soil layer at the passive side. The results showed that this adjustment is not applicable for any of the case studies. Only in one of the situations in the sensitivity analysis of one case

study did it appear that the placement of colloidal concrete could be applied. However, this involved a scenario where the top loads were placed further back from the sheet pile wall. Based on these findings, it can thus be concluded that placing colloidal concrete as soil layer at the passive side does not show any potential as a structural adjustment to strengthen an existing sheet pile wall.

- Add stability:
  - **Placing anchors above water**: The results showed that this adjustment leads to a satisfactory design for only one of the three case studies. For this case, the obtained failure mechanism was the failure of support mechanisms, indicating that the existing anchors would collapse. The sensitivity analysis of this case revealed that placing the anchors would still be applicable if the corrosion rate increased. Based on these findings, it can thus be concluded that placing anchors above the waterline can mainly be used if the failure mechanism of a sheet pile is the failure of support mechanisms. Since there was no case study that did not use anchors, no conclusion can be drawn about that situation.
  - **Placing underwater anchors**: The results showed that this adjustment leads to a satisfactory design for each case study, despite the fact that two different failure mechanisms were obtained for these cases. Moreover, the sensitivity analysis showed that it is an applicable adjustment for almost every scenario of each case study. However, the results also revealed that placing underwater anchors was not the preferred configuration for any case. Although assumptions are made for the financial and environmental data, this can be explained by its high costs compared to the other types of adjustments. These have now been assumed to be twice the costs of anchors placed above the waterline, but this factor may even be higher. Based on these findings, it can thus be concluded that placing anchors below the waterline has great potential to be used as structural adjustment, as it is not related to any specific failure mechanism and is also applicable in possible future situations. However, further research is needed to assess the financial and environmental data associated with this adjustment.

6.1.2. Conclusions of development decision support tool

The development statement and therefore the goal of this thesis was to develop a decision support tool that enables the direct determination of the preferred configuration of structural adjustments to existing quay walls, by applying the Preferendus that maximises the aggregated preference of multiple stakeholders while satisfying technical constraints. Although certain improvements are possible, this thesis concludes that the tool's development has been successful. The tool includes all needs and technical requirements, namely that the tool is only depending on input data, that it is applicable on each existing steel sheet pile, that it tests for failure mechanisms and that it uses an *a-priori* design optimisation method. Moreover, the tool has demonstrated direct added value, of which the three most valuable aspects will be highlighted:

- **Increased efficiency**: Firstly the tool enabled an increased efficiency in conducting a variants study of structural adjustments for an existing sheet pile wall. This eliminates the need to manually calculate each adjustment and its associated varying dimensions and evaluate failure mechanisms by trial and error. As a result of this increased efficiency, the tool enabled it to easily implement specific sheet pile information that becomes increasingly available during the preliminary design phase. The same holds for a sensitivity analysis, which because of the tool can be carried out easily. This enables the user of the tool to obtain more insight in both the current and possible future status of a sheet pile.
- **Financial and environmental impact insights**: Secondly, the tool enabled it to show the environmental and financial impact of all adjustments and combine this with the sheet pile calculations. As a result, this not only provides insight into whether a feasible design of a sheet pile has been created but immediately reveals what the associated ECI-price, CO_2 emissions and costs are as well. Moreover, another positive consequence of this is that the user of the tool no longer needs to consult other sustainability or financial experts, but has direct insight into these sums and results him- or herself.

- **Direct determination of preferred solution**: Lastly, by applying the *a-priori* design optimisation method of the Preferendus, the tool has enabled it to directly determine the preferred configuration of structural adjustments. This configuration contains the maximum aggregated preference score of the stakeholders involved and satisfies the technical constraints. As a result, it is immediately clear for the user of the tool which configuration of adjustments should be applied. This eliminates the need to analyse a number of variants afterwards and determine the preferred configuration *a-posteriori*.

In short, a tool has been created that is intended to be used during the preliminary design phase. This tool provides insight into which structural adjustments can be applied to make a design of an existing sheet pile satisfy. In addition, the tool is able to directly determine which configuration is the theoretically maximum preferred configuration. Thus, based on the above findings, this thesis concludes that the development of a decision support tool for existing quay walls has been successful.

6.2. Recommendations

Based on the project's findings, this thesis proposes several recommendations for follow-up research, each discussed in detail in the following section.

6.2.1. Perform lab tests to improve soil parameters

The sensitivity analyses conducted showed that by only improving the cohesion and friction angle of each soil layer by 3-6%, no structural adjustments were necessary at all to be able to withstand the future water bottom level. From a circular perspective this would be the most preferred solution to 'reinforce' a quay wall as the ECI-price and CO2 emissions would be equal to 0. Besides, also from a financial perspective it would still be cheaper compared to the new sheet pile situation. Although this improvement can not be guaranteed by conducting laboratory tests and these tests can be costly as well, it has the potential of being considered as preferred solution for each case study.

As stakeholders expected a configuration of structural adjustment to be the best solution, the finding that a possible improvement in soil parameters could be the best solution was unexpected. It therefore forms a parallel with the 'thinking, fast and slow' theory of Daniel Kahneman [38]. This theory distinguishes two systems of thought: the rapid and intuitive System 1, and the slower and logic System 2. The intuitive response - System 1 thinking - might have led to the assumption that applying structural adjustments should be considered as best option. However, the sensitivity analyses that are conducted from a systematic approach and logical reasoning - System 2 thinking - revealed that improving the soil parameters could be more preferred, which was unexpected. Especially as it is such an small improvement (3-6%), the analytical method shows the great impact of the soil parameters on the quay wall as a system. It therefore not only contradicts the assumption that applying structural adjustments are the best option, but also underscores the value of adopting a systematic approach in decision-making processes instead of relying on intuitive thinking.

Nevertheless, it should be noted that the improvement in cohesion and friction angle is applied on each soil layer in the sensitivity analysis of each case study. This is a condition that should therefore hold in practice as well. In addition, the improvement must first be proven by conducting lab tests, as these tests do not guarantee success. Because of these conditions, it is recommended to conduct a follow-up research whether it is possible to improve the cohesion and friction angle of soil layers by conducting these tests.

6.2.2. Follow-up research on applicability of underwater anchors

The results of each case study showed that placing UW anchors are applicable for each considered case. Moreover, the sensitivity analysis of each case showed that placing UW anchors are also applicable in potential future situations. This thesis could therefore conclude that UW anchors hold great potential as structural adjustment regarding the ability to increase the lifetime of existing quay walls. However, it should be noted that assumptions are used for the financial and environmental data for this adjustment. Since the costs have now been assumed to be twice the costs of anchors placed above the waterline, the results revealed that using them is expensive compared to the other considered adjustments. However, this cost factor might be even higher, given the uncertainties associated with placing anchors underwater. It is therefore recommended to look further into the costs of placing UW anchors. Based on this research it can then be obtained what the maximum price could be to be selected as preferred solution for a quay wall. Moreover, if the specific costs are determined and it is proven to be too expensive compared to other adjustments, it is recommended to do a follow-up research to find out if it can be made cheaper. As assumptions are made for the ECI-price and CO2 emissions as well, it is recommended to obtain these data more accurately as well. Finally in general, as research is currently still going on for UW anchors, it can be expected that more studies will be published in the coming years which could possible be used to improve this project as well.

6.2.3. Exploration of other optimisation methods

The results of each case study showed that only one type of structural adjustment was obtained as preferred configuration of adjustments, while the combinations of adjustments were tested as well. These combinations were tested because of the application of the Preferendus, which makes use of a GA to convert to the preferred solution. Due to the many iterations, the computational time of running this optimisation was heavily increased, which in total could rise up to 3 hours. Because of this computational time and because only individual adjustments are found as preferred configurations, the question is raised whether it makes sense to use the Preferendus and thus a GA within this domain. An option could for example be to simply calculate all possible configurations, both individual adjustments and the combinations of adjustments with varying parameters, called brute-force. However, then the preferred configuration will again be selected *a-posteriori* while the developed tool enabled it to select it directly because of the Preferendus. It is therefore recommended to explore other optimisation methods to include in the Preferendus, to still be able to determine the preferred configuration directly. One of those methods could for example be simulated annealing. While a genetic algorithm performs the calculations for an entire population from which the best results are selected, simulated annealing performs one calculation at a time and tries to improve the results from that point. Thus by applying simulated annealing, the computational time may be reduced while the same optimised results can be obtained. Moreover, using simulated annealing guarantees an optimal result, whereas when using a GA, this can not be proven. Since currently the preferred configuration is an optimised result, simulated annealing could further improve it to the actual optimum. It would therefore be recommended to start with simulated annealing when other optimisation methods are investigated. However, other optimisation methods could be explored as well.

6.2.4. Include variable costs and implementation risks

The cost data that currently is included in the tool, involves direct implementation costs which are material and equipment costs. The decision to include only these costs came from the aim of developing a generic tool applicable to all steel sheet pile walls. For variable costs such as time-dependent processes or personnel costs, there would have been a too wide range in these costs if they were incorporated in the tool. Besides, the possible implementation risks that exist for certain adjustments are currently missing in the tool either, while these risks can be expressed in costs as well. As a result, it is possible that the theoretically maximum preferred configuration has been determined while if that configuration were to be applied in practice, a lot of unforeseen costs would arise. Thus, it is recommended to include both the variable costs and the possible risks per adjustment in the tool to improve the tool in obtaining a more practically preferred result.

6.2.5. Variation of sheet pile calculation method

As explained, multiple calculations methods exist to calculate a sheet pile. Currently, the spring supported beam model is included in the tool as an integration with Dsheet from the Python script is used for the sheet pile calculations. Whereas this choice has been made because Dsheet is able to faster execute the calculations compared to other methods, it could occur that different preferred configurations are obtained when a different calculation method is integrated in the tool. For example, this can be PLAXIS which makes use of the finite element method and which has a built-in API to cooperate with Python as well. This makes it a useful alternative of Dsheet and it can potentially even improve the accuracy of the tool. It is therefore recommended that a follow-up research is conducted in which a tool is developed that uses PLAXIS instead of Dsheet, so that the added value of both can be compared and a choice can be made as to which should be used.

6.2.6. Include more structural adjustments in tool

Currently, five types of adjustments are included in the tool which are adding BIMS as soil layer, extending the sheet pile, placing a colloidal concrete layer, placing AW anchors and placing UW anchors. These can be classified in three options to strengthen a sheet pile, which are reducing the active soil stress, increasing the passive soil stress and adding stability. For each of those options however, more types of adjustments exist. Also, the results showed that some of the adjustments can be applied specifically if certain failure mechanisms are active at the tool. To therefore explore if this holds for other type of adjustments as well, it is recommended to include more adjustments in the tool.

6.2.7. Apply tool on different sheet piles outside of Tilburg

As the tool is originally developed to be used within project Rhombus UPSIDE, the tool has been applied on three sheet pile segments of industrial port Loven in Tilburg. However, the tool can be applied on any steel sheet pile and it is thus interesting to see if the same results are obtained when the tool is applied on different sheet piles outside of Tilburg. Especially as there may be other conditions there, such as the soil profiles. As this could improve the validation of the tool, it is recommended to apply the tool on sheet pile walls outside of Tilburg.

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A

New Sheet Pile Construction

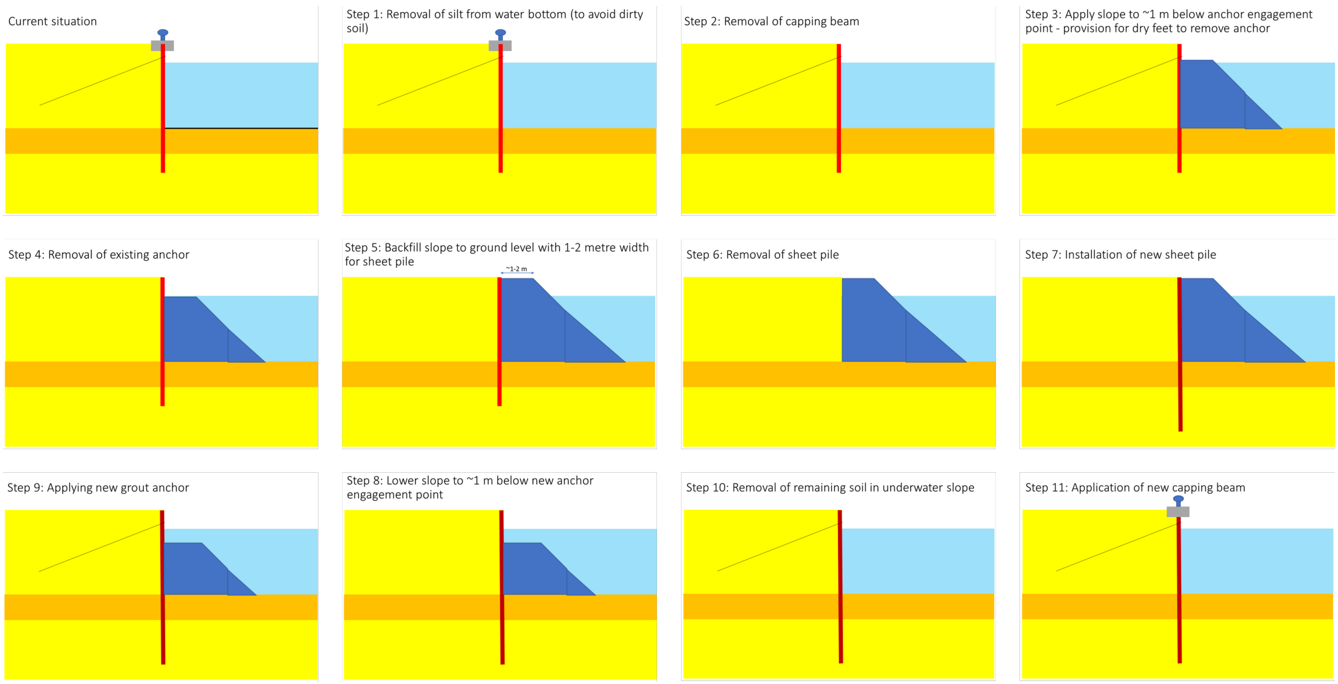

Figure A.1: Process of constructing a new sheet pile wall

Activity	ECI-price	CO2 emissions	Costs
Removal of silt	0.17 €/m³ silt	1.28 kg/m³ silt	15 €/m³ silt
Removal of capping beam	0.21 €/m quay	2.86 kg/m quay	50 €/m quay
Placing slope	1.50 €/m³ slope	11.05 kg/m³ slope	30 €/m³ slope
Removal of anchor	1.64 €/m anchor	19.40 kg/m anchor	650 €/anchor
Removal of sheet pile	0.44 €/m² sheet pile	3.32 kg/m² sheet pile	50 €/m² sheet pile
Placing new sheet pile	35.95 €/m² sheet pile	271.30 kg/m² sheet pile	1200 €/ton sheet pile
Placing new grout anchors	17.45 €/m anchor	206.47 kg/m anchor	2850 €/anchor
Removal of slope	0 €/m quay	0 kg/m quay	10 €/m quay
Placing new capping beam	0.84 €/m quay	11.44 kg/m quay	60 €/m quay

Table A.1: Financial and sustainability data for a new sheet pile construction

B

Data and Cross-sections of Case Studies

This appendix contains all data that is used to calculate the sheet piles of the case studies. Next to that, the original cross-sections of all sheet piles are included. First, quay wall Van Casteren will be provided. Hereafter, quay wall 28 is stated. Lastly, quay wall Versteijnen is highlighted.

B.1. Quay Wall Van Casteren

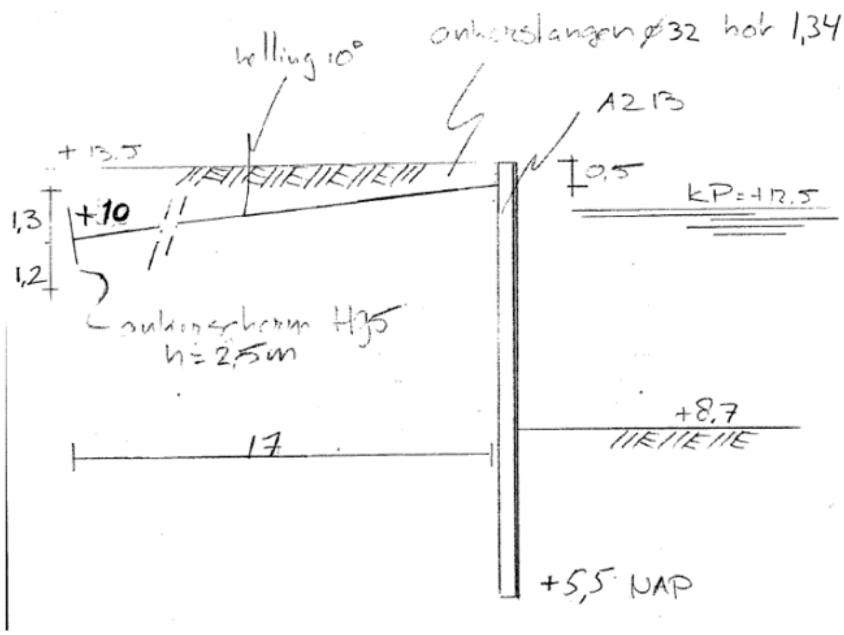

Figure B.1: Cross-section of sheet pile wall van Casteren

Soil type	Top level [+m N.A.P]	γ_d [kN/m³]	γ_n [kN/m³]	c' [kPa]	ϕ [degrees]	δ [degrees]	K1 [kN/m³]	K2 [kN/m³]	K3 [kN/m³]
Loose sand	13.50	17	19	0	30	20	12000	6000	3000
Moderate clay	12.00	17	17	5	22.50	15	5333	3333	1600
Solid sand	10.50	19	20	0	35	23.33	34000	17000	8500
Moderate clay	9.25	17	17	5	22.50	15	6000	4000	2000
Loose sand	8.00	17	17	0	30	20	14400	7200	3600
Solid sand	6.25	19	20	0	35	23.33	22000	11000	5500

Table B.1: Soil structure and characteristic soil parameters of Quay Wall Van Casteren

Condition	Definition	Unit
Lifespan		
Design year	2002	-
Current year	2023	-
New lifespan	50	years
Sheet Pile Conditions		
Sheet pile profile	AZ-13	-
Steel grade	S235	-
Length sheet pile	8.0	m
Original thickness	9.5	mm
Original section modulus	1300	cm^3/m
Anchor Conditions		
Anchor type	Ankerscherm	-
Anchor diameter	32	mm
Steel grade anchor	S500	-
Yield stress anchor	435	N/mm^2
Angle of anchor	10	degrees
Anchor length	17.25	m
Anchor point of engagement	13.00	m+N.A.P.
Center to center (c.t.c)	1.34	m
Surrounding Conditions		
Ground level	13.50	+m N.A.P.
Water level	12.50	+m N.A.P.
Water bottom level	8.70	+m N.A.P.
Future water bottom level	8.21	+m N.A.P.
Top Loads: metres behind sheet pile		
Crane load: 0.00 - 0.80m	160.00	kN/m^2
Crane load: 0.00 - 5.00m	25.00	kN/m^2
Sand storage: 5.00 - 40.00m	105.00	kN/m^2

Table B.2: Construction parameters of Quay Wall Van Casteren

B.2. Quay Wall 28

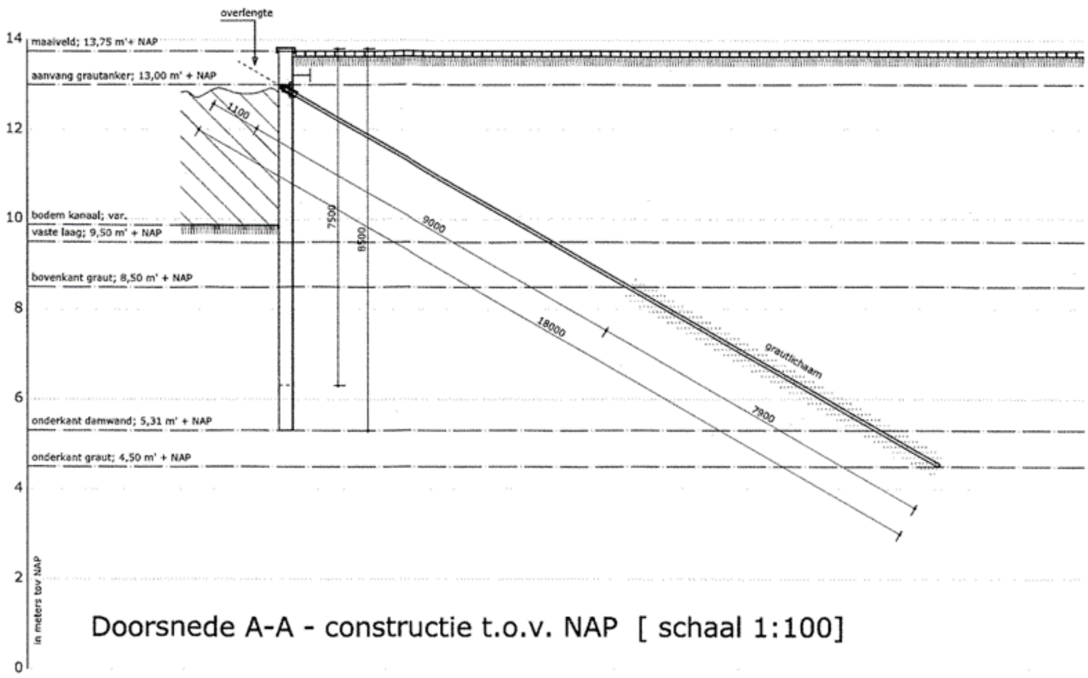

Figure B.2: Cross-section of sheet pile wall 28

Soil type	Top level [+m N.A.P]	γ_d [kN/m³]	γ_n [kN/m³]	c' [kPa]	ϕ [degrees]	δ [degrees]	K1 [kN/m³]	K2 [kN/m³]	K3 [kN/m³]
Solid sand	13.50	19	21	35.0	0	23.3	40000	20000	10000
Loose sand	12.40	17	19	30.0	0	20.0	12000	6000	3000
Solid clay	11.00	19	19	17.5	13	11.7	6000	4000	2000
Moderate sand	10.40	18	20	32.5	0	21.7	20000	10000	5000
Clayey silty sand	9.00	18	20	27.0	0	18.0	20000	10000	5000
Solid sand	8.50	19	21	35.0	0	23.3	40000	20000	10000
Clayey silty sand	5.00	18	20	27.0	0	18.0	20000	10000	5000
Solid sand	4.00	19	21	35.0	0	23.3	40000	20000	10000

Table B.3: Soil structure and characteristic soil parameters of Quay Wall 28

Condition	**Definition**	**Unit**
Lifespan		
Design year	2008	-
Current year	2023	-
New lifespan	50	years
Sheet Pile Conditions		
Sheet pile profile	BZ-IV-N	-
Steel grade	S355	-
Length sheet pile	8.19	m
Original thickness	14.0	mm
Original section modulus	2360	cm³/m
Anchor Conditions		
Anchor type	Groutanchor	-
Anchor diameter	56.0	mm
Steel grade anchor	S725	-
Yield stress anchor	630	N/mm²
Angle of anchor	27	degrees
Anchor length	16.90	m
Anchor point of engagement	13.00	m+N.A.P.
Center to center (c.t.c)	4.95	m
Surrounding Conditions		
Ground level	13.50	+m N.A.P.
Water level	12.50	+m N.A.P.
Water bottom level	9.00	+m N.A.P.
Future water bottom level	8.21	+m N.A.P.
Top Loads: metres behind sheet pile		
Crane load: 0.50 - 1.35m	350.00	kN/m²
Crane load: 6.50 - 7.25m	77.00	kN/m²

Table B.4: Construction parameters of Quay Wall 28

B.3. Quay Wall Versteijnen

Soil type	Top level [+m N.A.P]	γ_d [kN/m³]	γ_n [kN/m³]	c' [kPa]	ϕ [degrees]	δ [degrees]	K1 [kN/m³]	K2 [kN/m³]	K3 [kN/m³]
Loose sand	13.50	17	19	0	30.0	20.0	16000	8000	4000
Moderate clay	11.20	17	17	5	17.50	11.60	4000	2000	800
Loose sand	9.80	17	19	0	30.0	20.0	13600	6800	3400
Sand	9.00	18	20	0	32.50	21.67	26000	13000	6500

Table B.5: Soil structure and characteristic soil parameters of Quay Wall Versteijnen

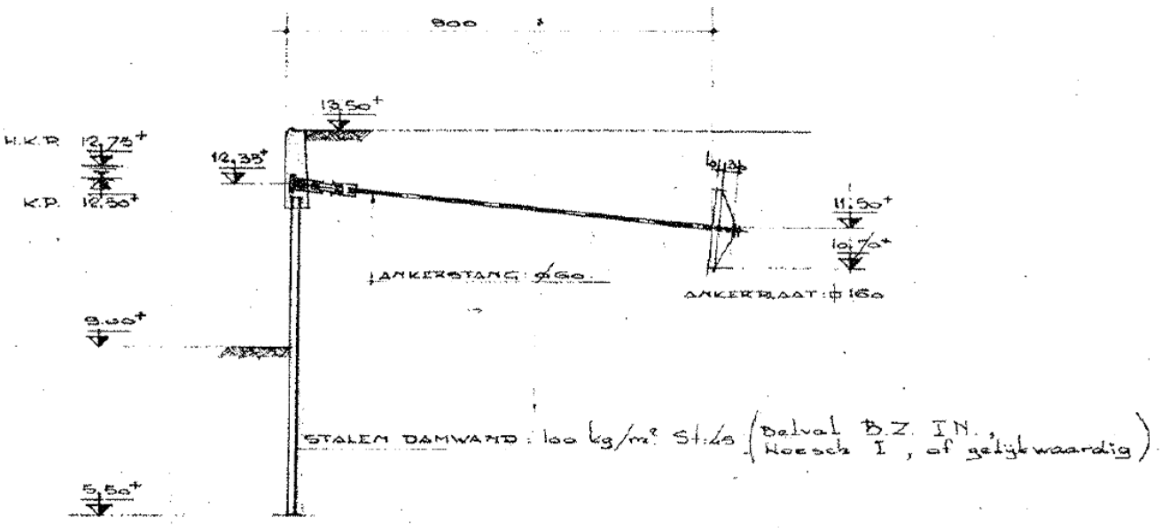

Figure B.3: Cross-section of sheet pile wall Versteijnen

Condition	**Definition**	**Unit**
Lifespan		
Design year	1966	-
Current year	2023	-
New lifespan	50	years
Sheet Pile Conditions		
Sheet pile profile	BZ-I-N	-
Steel grade	S275	-
Length sheet pile	8.00	m
Original thickness	8.0	mm
Original section modulus	700	cm^3/m
Anchor Conditions		
Anchor type	Ankerscherm	-
Anchor diameter	60	mm
Steel grade anchor	S355	-
Yield stress anchor	308.70	N/mm^2
Angle of anchor	5.40	degrees
Anchor length	9.00	m
Anchor point of engagement	12.35	m+N.A.P.
Center to center (c.t.c)	4.00	m
Surrounding Conditions		
Ground level	13.50	+m N.A.P.
Water level	12.50	+m N.A.P.
Water bottom level	9.00	+m N.A.P.
Future water bottom level	8.21	+m N.A.P.
Top Loads: metres behind sheet pile		
Uniform load: 0.00 - 3.00m	20.00	kN/m^2
Container load: 0.00 - 3.00m	45.00	kN/m^2

Table B.6: Construction parameters of Quay Wall Versteijnen