Sustainability assessment of quay wall development in the Port of Rotterdam

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Cover image: quay wall development at the HHTT terminal in the Port of Rotterdam (PoR, 2019)

Preface

This thesis represents my graduation work as part of the master program Hydraulic Engineering at the Delft University of Technology. During the nine months of my graduation internship at the Port of Rotterdam, I was able to apply my technical knowledge to practical actions and enriched myself with new knowledge on sustainability and port development. However, I could not have done this without the help of many people and will therefore take a moment to thank them. First of all I want to express my gratitude to my supervisors at the Port of Rotterdam, Caroline Bosschieter and Erik Broos, who shared their insights and provided valuable feedback throughout the whole process. Their positive energy and devotion to sustainability was inspiring and has helped my to finish this report. I want to thank the rest of my thesis committee: Mark van Koningsveld, Poonam Taneja and Jan Anne Annema for providing new knowledge on how to achieve targets, their insights and their feedback. I want to thank Vincent Swinkels for sharing his experience in sustainable management, and Peter Quist and Marinus Aalberts of Witteveen & Bos for providing their network. I want to thank my family and friends for motivating me. The last group I want to thank is all the remaining people that helped me throughout the process.

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Abstract

The current social climate in which sustainable awareness is prioritized, is affecting the port sector. In new-to-develop ports and in the expansion and maintenance of existing ports, implementing sustainability is encouraged. However, applying sustainability is not self-evident. In order to achieve sustainability targets and to comply with the environmental laws, port authorities should be able to define and quantify sustainability. This research aims to define, quantify and improve sustainability in quay wall development, which is a most-common infrastructure component in port development.

The first step of this research is to develop a framework to assess port infrastructure on its sustainability performance. Following the Frame of Reference method (van Koningsveld & Mulder, 2004), the Framework of Sustainable Port Infrastructure (FoSPI) has been developed. The FoSPI consists of fourteen aspects of sustainability that has been derived from literature, which can be applied to all port infrastructure assets. The aspects are the following:

Water pollutants	Energy	Cultural
Soil pollutants	Biological ecosystems	Future resiliency
Air pollutants	Water consumption	Traffic management
Light pollutants	Employment	Stakeholders involvement
Noise	Waste management	

Each aspect includes one of more targets that are determined by the company and/or by the location's regulations. Furthermore each of these targets requires their own quantification tool, reference base, intervention measures and evaluation procedure. These are dependent on the location and the type of port infrastructure asset. If the target(s) is (are) achieved, this would mean that the infrastructure has reached a more sustainable level on this aspect. All fourteen aspects should meet their target(s) to conclude that the infrastructure has reached a more sustainable level. The FoSPI has been applied to quay wall development in the Port of Rotterdam (PoR) and this resulted that only four out of fourteen can be specified to be further assessed. The remaining eleven aspects should be investigated further to assess quay wall development in total. As the PoR has prioritized Greenhouse Gas (GHG) emissions (this was based on literature and interviews within the port), this thesis will focus on the the GHG emissions of the aspect 'Air pollutants' in quay wall development. Nevertheless, the way this GHG target was included in the analysis can also be used for other sustainability aspects for which the company has a target.

The second step of the research is to determine the actual value of GHG emission of a current quay wall project. To do this, an evaluation procedure and quantification tool was selected. The author proposed to quantify a 100 meter standard short sea quay wall of the PoR with a life time of 100 years as the reference base case. A tool is selected that is able to quantify GHG emission, is objective and represents actual quay wall development. Using literature sources, the tool DuboCalc is proposed, because it is based on the life cycle analysis, is sector specific and is simplified (compared to other tools). However, the tool should be handled with a certain caution. The research showed that the results are not 100 % reproducible. However, when a thorough check and evaluation is part of the process, the results will converge. In the research, the results of the exercise had a percentage relative range of 28 %, but after a thorough check and evaluation, the second results achieved a range of 8 %. Secondly, DuboCalc doesn't include all quay wall objects, hence it will give an approximately GHG emission. The tool has room for improvements. The tool is used to quantify the reference base by using an actual PoR project, the HHTT terminal as the case study. This resulted in a total emission of 1.9 kt of CO_2-eq for a 100 meter standard PoR short sea quay wall with a life time of 100 years.

The third step of this research is to determine how the PoR can reach their GHG targets. The reduction measures to achieve the target of being climate neutrality in 2050, are discussed. A summation of suitable measures from multiple reports of PoR is made. Using literature, DuboCalc data and the case study, the most suitable

measures were quantified for the PoR. It is concluded that the PoR should focus on the largest contributors of GHG emission. The following actions are advised:

- As from 2020, renewable energy could be used for the Impressed Current Cathodic Protection (ICCP) which could lead to 15% reduction in GHG emissions over the quay wall's life cycle. The transition from fossil electricity to renewable electricity is without extra investment costs.
- Secondly, using renewable energy instead of diesel for the temporary drainage systems will reduce the emission with 14 %. Including previous actions a total reduction of 29 % is achieved. The costs of the amount of renewable electricity is lower than the required amount of diesel.
- Thirdly, if the PoR will invest approx. 170 euro for every saved CO_2-eq, Hydrotreated Vegetable Oil (HVO) can be used as an alternative fuel for dredging to reduce emission with 8 %. Including previous actions a total reduction of 37 % is achieved.
- Further research could be done in alternative designs. This could lead to a reduction in concrete and steel use, as they are the larger contributors. Alternative designs includes quay walls made out of Recycled High Density PolyEthylene (RE-HDPE), smaller dimensions of steel piles and prefab concrete quay walls with geo-polymer-based-cements.
- The evaluation procedure in which the quay wall is monitored every five years, could be implemented. This will help to evaluate the applied intervention measures and to oversee if the targets are going to be achieved. It will be part of the strategical planning of the PoR.
- Furthermore, the PoR could encourage the constructors to use electrified transport (on commercial scale available around 2025) and machinery (on commercial scale available around 2030) to reduce emission with 3 % and 11 % respectively. Including previous actions a total reduction of 51 % is achieved.
- Finally, anticipating long term technical innovation in concrete with Carbon Capture and Storage (CCS) (on commercial scale available around 2030), hydrogen as dredging fuel (on commercial scale available around 2050) and steel with hydrogen as reduction-agent (on commercial scale available around 2050). This could reduce emission with 9%, 10 % and 24 % respectively. Including previous actions, except use of HVO, a total reduction of 86 % is achieved.

Although the calculated reduction of GHG emission in 2050 does not satisfy the target of being climate neutral, the potential reduction of 86 % is a considerable improvement.

For the PoR case, the described three-step approach has led to an improved insight in sustainability of quay wall development, and to specific recommendations to reduce the GHG emission. The method is applied to quay walls and to the PoR, but it can be applied generally as well, provided that the targets are adapted to the concerned company and its location, and the quantification tool, the reference base and the intervention measures are adapted to the type of asset and the location.

The research does contain various limitations, namely only one target of one aspect could have been investigated in depth, although the influence of the proposed solutions on the other aspects is not considered. It is recommended that this influence should be determined to see if the targets of other aspects of sustainability are met as well.

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List of abbreviations

AAPA - American Association of Port Authorities
BBS - Bed, Bank and Shore
BEVs - Battery Electric Vehicles
BF-BOF - Blast Furnaces to Basic Oxygen Furnace
BREEAM - Building Research Establishment Environmental Assessment Method
CCS - Carbon Capture and Storage
CEEQUAL - Civil Engineering Environmental Quality Assessment and Award Scheme
CO_2-eq - Carbon dioxide equivalents
DRI - Direct Reduced Iron
EAF - Electric Arc Furnaces
EIA - Environmental Impact Assessment
EPA - Environmental Protection Agency
EPD - Environmental Product Declaration
ESPO - European Sea Ports Organisation
FCEVs - Fuel Cell Electric Vehicles
FoR - Frame of Reference
FoSPI - Framework of Sustainable Port Infrastructure
GHG - Green House Gases
HVO - Hydrotreated Vegetable Oil
IAPH - International Association of Ports and Harbors
ICCP - Impressed Current Cathodic Protection
ICE - Internal Combustion Engines
IFC - International Finance Corporation
IFC - PS - International Finance Corporation - Performance Standard
IFC - EHS - International Finance Corporation - Environmental, Health and Safety
LCA - Life Cycle Assessment
LNG - Liquefied Natural Gas
MDO - Marine Diesel Oil
NMD - Nationale Milieu Database
OECD - Organisation for Economic Co-operation and Development
PIANC - Permanent International Commission for Navigation Congresses
PoR - Port of Rotterdam
PoR-AM - Port of Rotterdam - Asset Management
PoR-EM - Port of Rotterdam - Environmental Management
PoR-PD - Port of Rotterdam -Port Development
RE - HDPE - Recycled High Density Polyethylene
SBK - Stichting Bouwkwaliteit
SFRC - Steel Fibre-Reinforced Concrete
UNCSD - United Nations Conference on Sustainable Development
UNEP - United Nations Environment Program
UN-SDG - United Nations - Sustainability Development Goals
USACE - United States Army Corps of Engineers
WWF - World Wide Fund for Nature

1 Introduction

1.1. Background

From the beginning of ports, estuaries have always been an important area for port development. The presence of river(s) made hinterland connection simple and the oceans made international ambitions possible. The policy towards estuaries was always to maximize the specific use, hence to maximize port activity (Boerema & Meire, 2016). Channels were deepened and widened to improve shipping navigation and quay walls were constructed for port activity. Due to the increase of population in these fragile areas, dikes and seawalls were built to protect against flooding. This had its impact: worldwide large estuary habitats have been lost or degraded. Human activity attracted new industries as well, causing a poor living standard with unhealthy emissions (Turner et al., 2000). Nowadays port and its related industries have a high impact on global warming and livability. This caused the growing demand to include sustainability in ports and port development.

Sustainable port development is a reoccurring subject in the port engineering field. Different studies have been done (e.g. (PIANC, 2008), (Vellinga, de Kaene, Rijks, Schrerrer, & Uelman, 2014)) to quantify this concept. Various frameworks including international standards are made available for sustainable port engineering but an universal consensus on the definition of sustainability is missing. This is due to the relation to context, place and time (Vellinga, Slinger, Taneja, & Vreugdenhill, 2017). A general used definition of the Brundtland Commission gives the following definition for port sustainability: "Business strategies and activities that meet the current and future needs of the port and its stakeholders, while protecting and sustaining human and natural resources" (AAPA, 2007).

Literature related to port sustainability encourages universal guidelines (PIANC, 2008), (Vellinga et al., 2014). It can be accomplished through embracing the perspectives of engineering, ecosystem services and governance in an integrated approach (Vellinga et al., 2017). The acknowledgement of investigating the sustainability aspects across the entire value chain is critical: from infrastructure design to the end-of-life phase should be considered. This is also known as the life cycle. Organizations like AAPA, IAPH, ESPO, OECD, PIANC, EPA, UNEP, UNCSD, USACE and WWF (see list of abbreviations) are frequently updating their international guidelines for sustainable port development (Taneja & Vellinga, 2018).

Nowadays ports are still being build or expanded, and the sustainable development is not the first priority. That is why research is ongoing and guidelines are constantly updated. To achieve sustainability, the stakeholders that have an impact on port activities need to act. In this report, the landlord port authority perspective is considered. A landlord port is by definition the owner and manager of the port area. One of its responsibilities is the development of primary port infrastructures in the area. This means the authority can include sustainability as criteria for port development. In marine port infrastructure projects, various structures are being developed. Quay walls are one of the most essential components of port infrastructure and with growing volumes of cargo and increasing vessel size, the demand on these structures is increasing. It is a hard engineering structure that is part of almost every port infrastructure project. A more sustainable life cycle of a quay wall will increase the sustainability performance of the port projects and the port in total.

1.2. Problem statement

Despite the continuous process of determining sustainability in port development, in reality the concept 'sustainability' is still considered vague and difficult to execute in port projects. This is due to the wide ranging definition of sustainability and due to the lack of an objective sustainability performance assessment relevant to port development that contains the full life cycle. The context of this assessment should be universal, but when translating to operational actions to improve sustainability, the types of structures are too different to cover universally. That is why the focus will lay on quay wall development in this research. The first problem is that it is not known how a quay wall can be assessed on sustainability. In addition, the related sustainability targets are not determined.

Secondly, it is not known if the current existing tools can quantify the prioritized sustainability topics in an objective way. This is the scientific knowledge gap. The moment that a quay wall can be objectively assessed on sustainability, the following problem occurs: improving the sustainability is difficult to integrate in the decision making processes. Although some topics of sustainability are commonly used in the vision of port authorities, the intervention with measures to achieve the sustainability targets, is seen as complicated. At the Port of Rotterdam (PoR), sustainability is not fully integrated in the decision making process of quay wall projects. This causes a mismatch between the future desired situation (the targets) and the current existing standard infrastructure designs.

1.3. Objectives and research questions

The first objective is to achieve an approach to objectively assess the sustainability performance of port infrastructure projects. This approach is applied to quay wall development in the PoR. Thereafter, a prioritized aspect by the PoR is further elaborated. This leads to the second objective to consider applicable solutions for the prioritized topics. These solutions include intervention measures that will improve sustainability of the quay wall. This results in the following objectives:

Objectives:

- Objectively assess the sustainability performance of quay wall development projects in the Port of Rotterdam.
- Recommend applicable solutions that could increase the sustainability performance of quay walls in the Port of Rotterdam. Hence to achieve the desired sustainability targets.

To achieve these objectives, the following main research questions are considered:

1. **How can the sustainable performance of a quay wall during its life cycle be objectively assessed?**
    - How is the life cycle of a quay wall defined?
    - Which method for assessment and management of sustainability can be applied to quay walls and which method is most suitable?
    - Which are the prioritized aspects of sustainability for the Port of Rotterdam?
    - To what level has each of these aspects been specified for the Port of Rotterdam?
2. **Based on the selected method in research Question 1, what is the sustainability performance of a quay wall in the Port of Rotterdam?**
    - Which calculation tools can be used off the shelf to objectively asses the prioritized aspects in the Port of Rotterdam?
    - What is the order of magnitude of the bias of the selected application and how can this order be reduced?
    - For which sustainability aspect is further specification needed?
    - What is the sustainability performance of the PoR standard quay wall?

3. **How can the Port of Rotterdam achieve their sustainability targets related to quay wall projects?**
    - Which sustainability measures could be proposed that will improve a project's sustainability performance for the prioritized aspects?
    - After implementing the proposed measures, will the PoR be able to achieve the sustainability targets on the prioritized aspects?

1.4. Research methodology

The research methodology outlines the various actions that are taken for this report. This study touches different engineering fields and it is written in close cooperation with the PoR. This has caused the study to be conducted following multiple methods.

To answer the research questions and the sub research questions, different phases can be detected throughout the report. The first phase is the information that has been collected. The data collecting has been done by consulting literature, by conducting interviews and by sending out a questionnaire. The second phase is the analysis in which different methods and a quantification tool, are used. Applying the knowledge on an actual situation is defined in phase three. This situation is an existing quay wall project located in the PoR. The fourth phase is the final phase in which discussions, conclusions and recommendations are made. The phases will be explained in more detail below. Figure 1.1 visualizes the different phases, the research questions and the chapters in which the different phases are discussed.

Data collection
The data has been collected by using literature sources, conducting interviews with PoR personnel and dredging firms, and sending out a questionnaire that has been completed by the port technical consultants.

The literature study gives a present overview of sustainability in ports, the existing quantification tools and the possible intervention measures. The literature that is consulted was found in books, internal and external reports of the PoR, TU Delft reports and web pages. The following information came from the literature study:

- Related to research question 1:
    - It defined the life cycle of quay walls and delivered a definition of sustainability, in general and sector specific (Paragraph 2.2).
    - It provided a method to assess sustainability in a systematical and objective manner (Paragraph 2.3).
    - It showed the different kinds of quay walls and identified the different sustainability targets, objectives, intervention measures, evaluation procedures and quantification possibilities (Paragraph 2.4).
    - It provided the prioritized sustainability topics of the PoR and its specifications (Paragraph: 3.2 and 3.3)
- Related to research question 2:
    - It resulted in an overview of the different sustainability quantification tools (Paragraph 4.3)
    - It facilitated the input data of the case study (Paragraph 5.2)
- Related to research question 3:
    - It identified the different intervention measures and its application costs (Chapter 6)

To answer research question 1, interviews were conducted with PoR personnel. They identified the most prioritized sustainability topics for the PoR. The choice was made to have an interview pool that consisted of seniors of different PoR's departments, to provide a more uniform representation. The interviewees are from the department of Port Development (PoR-PD), Environmental Management (PoR-EM), Finance and General Management. This is further discussed in Chapter 3. The interviews with the dredging companies gave a more realistic view of what is needed to execute sustainability targets, as they cause a large part of the emissions.

To answer research question 2, a questionnaire has been made by the author and four technical consultancy firms were asked to answer the questions. The four technical consultants are experts in sustainability and infrastructure projects. The questionnaire consists of two parts. The first part is a calculation that has to be made using an existing quantification tool (DuboCalc). The results from this part are used to determine the objectivity of the tool. The second part consists of evaluation questions about the assumptions that has been made by the consultants in the calculations and about the tool's representation of quay wall development. This can be found in Chapter 4.

Analysis

During the analysis, the existing literature on infrastructure's sustainability is looked into. This is done by performing the cross check method. A cross check is by definition a check that can be performed with data or reports from various sources to determine validity or accuracy. As a result, fourteen aspects of sustainability related to port infrastructure development have been determined. According to Laboyrie et al. (2018), an applicable method to assess sustainability for civil engineering structures should systematically identify, investigate and evaluate positive and negative sustainability effects. The Frame of Reference (FoR) is the suggested management method to use. This approach connects strategic -, and operational objectives and details each of them separately. With the fourteen aspects and the FoR method, a framework for assessment of sustainability of port infrastructure is set up. This framework will be applied to quay wall development in the PoR and will answer research question 1. This will be further discussed in Chapter 2.

The results of the questionnaire are analyzed to give an indication of the objectivity and the representation of the existing quantification tool (DuboCalc). Secondly, after evaluation with the corresponded technical consultancy firms, recommendations to improve the reproducibility and the representation are given. This will be used to answer research question 2 and can be found in Chapter 4.

Applying the Framework on an actual situation: case study

To answer research question 2 and 3, the HES Hartel Tank Terminal (HHTT) is used as the case study. In this terminal, the standard short sea quay wall design of the PoR is applied. With internal reports and the quantification tool, the current situation of the case study for the prioritized sustainability topic can be determined. This is done in Chapter 5. Secondly, the intervention measures are applied to the case study in Chapter 6.

Final phase

In the final phase, the findings are discussed and the conclusion and recommendations are made. This will be further elaborated in Chapter 7.

1.5. Report outline

The report outline is visualized in Figure 1.1 as well. Research question 1 will be answered in Chapter 2 and 3. In these Chapters, the approach to define the sustainable performance of a quay wall during its life cycle is explained. In Chapter 4 and 5 research question 2 will be answered. In Chapter 4 the existing quantification tool will be assessed on its ability to quantify, its objectivity and its representation. In Chapter 5 the tool will be used to calculate the current state of a quay wall. In Chapter 6 the possible interventions measures are examined and applied to the case study. This will result in answering research Question 3. In Chapter 7, the findings are discussed and the conclusion and recommendations will be given.

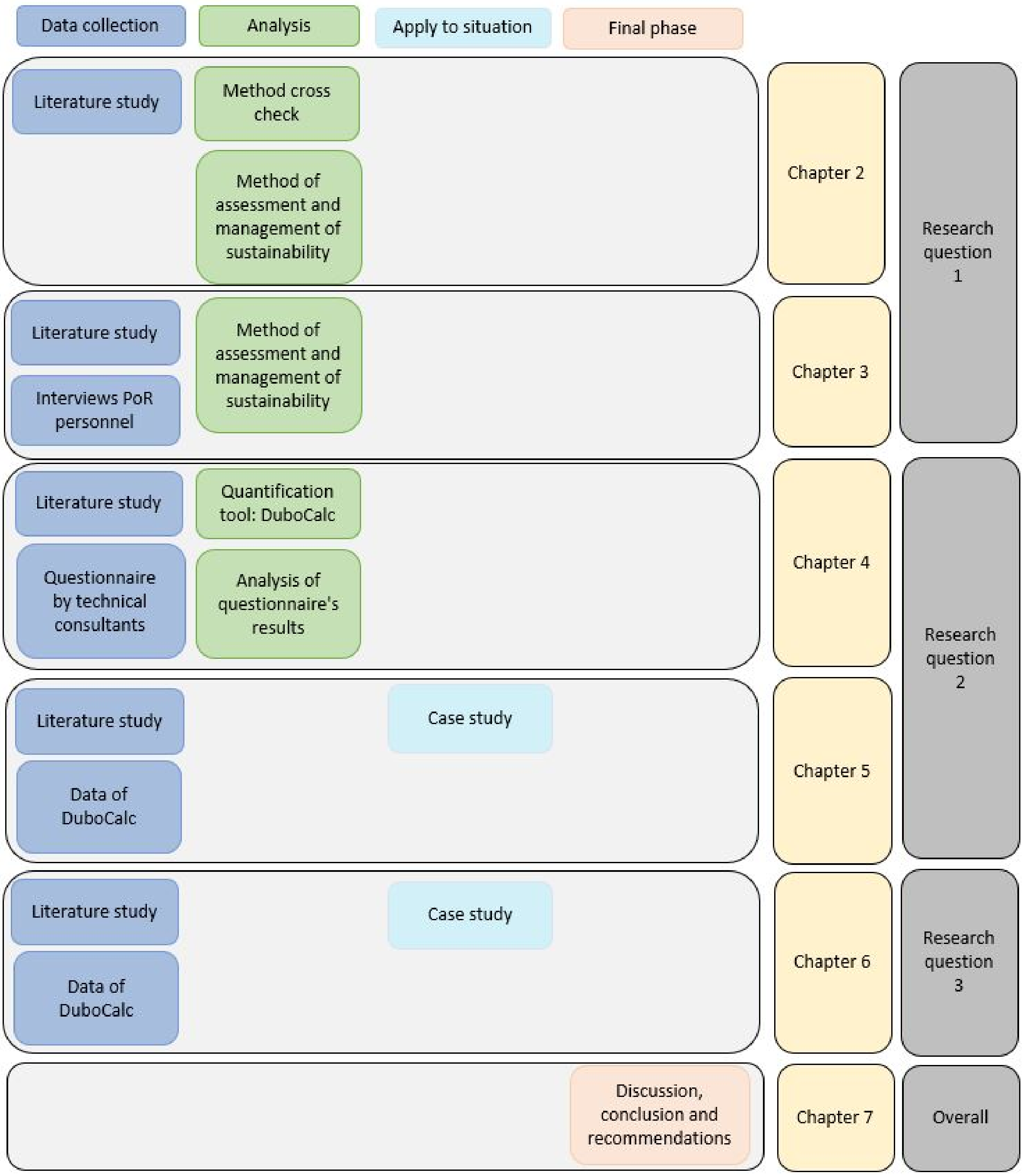


Figure 1.1: Methodology structure and lay out of the report.

2

The assessment of sustainability of quay wall projects

2.1. Introduction in the sustainability assessment

In this Chapter the sustainability assessment of quay wall development is discussed. In Paragraphs 2.2, the literature on life cycle assessment and sustainability related to port infrastructure is considered. This results in fourteen aspects of sustainability. In Paragraph 2.3, a method is proposed to assess sustainability objectively and is used to develop a framework for the assessment of sustainability of port infrastructure. In Paragraph 2.4, this developed framework is applied to assess quay wall development in the PoR.

2.2. The definition of sustainability related to port infrastructure assets

2.2.1. Life cycle assessment

To define sustainability for port infrastructure assets during its life cycle, it is necessary to determine the life cycle. According to code NEN-EN-ISO 14040:2006 (NEN, 2006), the life cycle assessment (LCA) is developed to better understand and address the possible environmental impacts associated with products and services. The LCA can assist in identifying opportunities to improve the environmental performance of products and services at various points in their life cycle. For this research, the terminology used in code NEN-EN-ISO 14040:2006, is applied to the development of port infrastructure. The LCA considers the entire life cycle of a product, starting from raw material extraction and acquisition, through energy and material production and manufacturing, to use and end of life treatment, and final disposal. This results in a systematic overview in which the shifting of a potential environmental burden between life cycle stages or individual processes can be identified and where possible, avoided.

The ISO code advises to determine the multiple steps in the life cycle of a product. Separating the life cycle of port infrastructure into several phases will help to identify the processes and products that exists in each phase. Figure 2.1 visualizes the complete life cycle for ports and navigation infrastructure (PIANC, 2019).

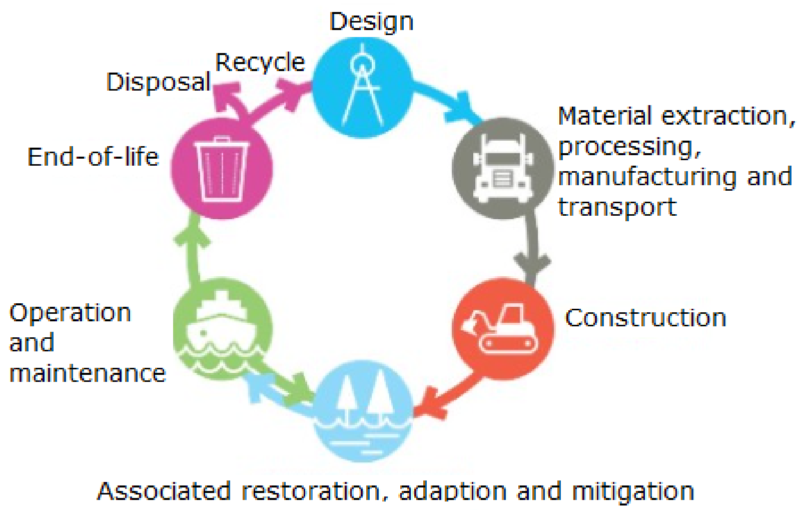


Figure 2.1: The life cycle for ports and navigation infrastructure and projects. Figure based on PIANC (2019).

According to Figure 2.1, the first phase is the design phase. In developed countries however, entirely new construction is less common. Renovation or expansion of existing facilities is more reasonable. Hence the design phase is partly the result of recycling as can be seen in Figure 2.1. The next phase is defined as the material extraction, processing, manufacturing and transport. In this phase, the acquisition of raw materials, input and output in the manufacturing and processing sequence and distribution of materials that are used in port infrastructure development, are considered. In this phase, the fuel and electricity used for machinery are included as well. The following phase is the construction phase in which the operational practices are translated. This includes the use of products, fuels and electricity. Construction is frequently contracted to a third party (i.e. contractor), hence the port authority has less control in the decision making in this phase. Be that as it may, contract mechanisms that include sustainability aspects, can be applied to increase the control. The next phase is the associated restoration, adaptation and mitigation phase. Measures during this phase are related with changing physical, regulatory and business environments. This phase includes maintenance of objects. The operation and maintenance phase is the longest time period of port infrastructure. In the last phase, namely the end-of-life phase, the process of decommissioning the port infrastructure is considered.

According to PIANC (2019), the phases should be reorganized into common infrastructure phases. Figure 2.2 shows the new reorganized phases. However, all business related activities by a third party (= operations) that are due to the present port infrastructure are out of scope for this research.

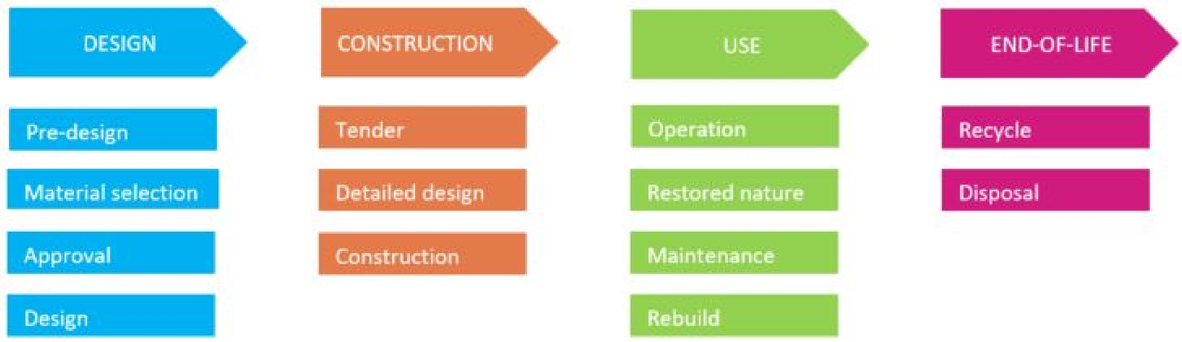


Figure 2.2: The phases related to the LCA of ports and navigation infrastructure. Figure based on PIANC (2019).

2.2.2. Literature on sustainability related to port development

Secondly, sustainability in relation to port infrastructure development should be defined. The flow system, described by Sotiriadou (2019), consists of the general activities in terms of port development. The activities are arranged into the corresponding life cycle phases. This flow system is described in Appendix A.1. Most of these in- and outflow components are related to environmental pollution. From these flows, the following aspects can be found:

Water pollutants	Noise	Employment
Soil pollutants	Energy	Waste management
Air pollutants	Biological ecosystems	
Light pollutants	Water consumption	

These aspects give a first impression of the sustainable performance. Secondly, various existing frameworks and guidelines are consulted to see how they interpret sustainability. A description of the considered tools and guidelines are listed below. Their corresponding criteria can be found in Appendix A.2. Some criteria is not applicable to the development of port infrastructure and they are hereby neglected. The reasoning can be found in Appendix A.2 as well. The applicable criteria are taken into account further during the cross check.

United Nations - Sustainability Development Goals

These guidelines of the United Nations consists of seventeen goals which attempts to encourage sustainable development. The UN SDG's are a commonly-used set of guidelines which form the foundation of companies' sustainability goals (United Nations, 2018).

International Finance Corporation

The International Finance Corporation (IFC) is the largest development institution of the world. It is part of the World Bank Group and focuses on the private sector in developing countries. According to World Bank Group (2017a), it offers products and services to improve markets that address the biggest development challenges of the present. It applies financial resources, technical expertise, global experience, and innovative thinking to help clients and partners overcome financial, operational, and other challenges. In 2012, the IFC published the IFC's Sustainability Framework. It includes the Performance Standards (PS) which are used as a benchmark when working with clients. It defines IFC clients' responsibilities for managing their environmental and social risks.

In addition, the World Bank Group have set up Environmental, Health, and Safety Guidelines (EHS Guidelines). They are industry-specific reference documents with examples of Good International Industry Practice. They refer to the IFC's Performance Standards. They exist of performance levels and measures that are accepted by the World Bank Group World Bank Group (2017a). A report is written including the EHS for ports, harbours and terminals. It consists of an environmental part and a social part.

BREEAM

Building Research Establishment Environmental Assessment Method (BREEAM) is a method of assessing, rating, and certifying the sustainability of buildings. BREEAM is an assessment using scientifically based sustainability metrics and indices that covers a range of environmental issues. Its categories evaluate energy and water use, health and well-being, pollution, transport, materials, waste, ecology and management processes. Buildings are rated and certified on a scale of 'Pass', 'Good', 'Very Good', 'Excellent' and 'Outstanding'. It is carried out by independent, licensed assessors (BREEAM, 2014).

CEEQUAL

The Civil Engineering Environmental Quality Assessment and Award Scheme (CEEQUAL) assesses infrastructure projects across the whole civil sector on their sustainability (CEEQUAL, 2019). This scheme rating system is comparable with BREEAM.

Ambitieweb

The Dutch Green Deal Duurzaam GWW initiative has the goal that all Ground, Road, and Water construction projects will follow the approach plan 'Aanpak Duurzaam GWW' in the planning-, building, and maintenance phase in 2020. Following this approach will lead to a sustainable sector with a balance between People, Planet and Prosperity (Duurzaam GWW, 2019). Working together following the guidelines, will encourage to make sustainable projects as business as usual and will improve sustainable projects in the future. Sixty parties of the Rail, Road and Hydraulic engineering branch already signed the Green Deal Duurzaam GWW.

2.2.3. Results of the cross check

The in- and outflows and the sustainability criteria from the various guidelines as described above, are compared. This is done using the cross check method. A cross check is by definition a check of data from various sources to determine validity. In this report, the validity of the sustainable topics for port infrastructure is checked. As a result, all the aspects can be defined. This cross-check can be found in Appendix A.3. The in- and outflow components did not match with the criteria from the various guidelines. Missing aspects were cultural, future resiliency, traffic management and stakeholders involvement. All together, fourteen aspects are ultimately defined and categorized as the following:

Water pollutants	Energy	Cultural
Soil pollutants	Biological ecosystems	Future resiliency
Air pollutants	Water consumption	Traffic management
Light pollutants	Employment	Stakeholders involvement
Noise	Waste management	

These 14 aspects define sustainability in port infrastructure development and will be called the aspects of sustainability.

2.3. The assessment framework

2.3.1. Method for assessment and management of sustainability

To assess port infrastructure development on the achieved fourteen aspects of sustainability, a formal procedure should be followed. A standardized procedure in infrastructure projects is the Environmental Impact Assessment (EIA) (Laboyrie et al., 2018). An EIA is a legal process to systematically identify, investigate and evaluate positive and negative sustainability effects. It includes the interests of various stakeholders. However, it is important to strive to be fully transparent and objective. In an EIA it is not directly highlighted which steps should be made to reduce the impact, hence it is unclear how to achieve a desired target. According to Laboyrie et al. (2018), a systematic approach to describe objectives and detail each of them into a management framework, is needed. In addition, an approach to connect strategic -, and operational objectives and an underlying decision framework is needed. The 'Frame of Reference' method, developed by van Koningsveld and Mulder (2004), is such an approach and will be used in this report. Figure 2.3 visualizes the method.

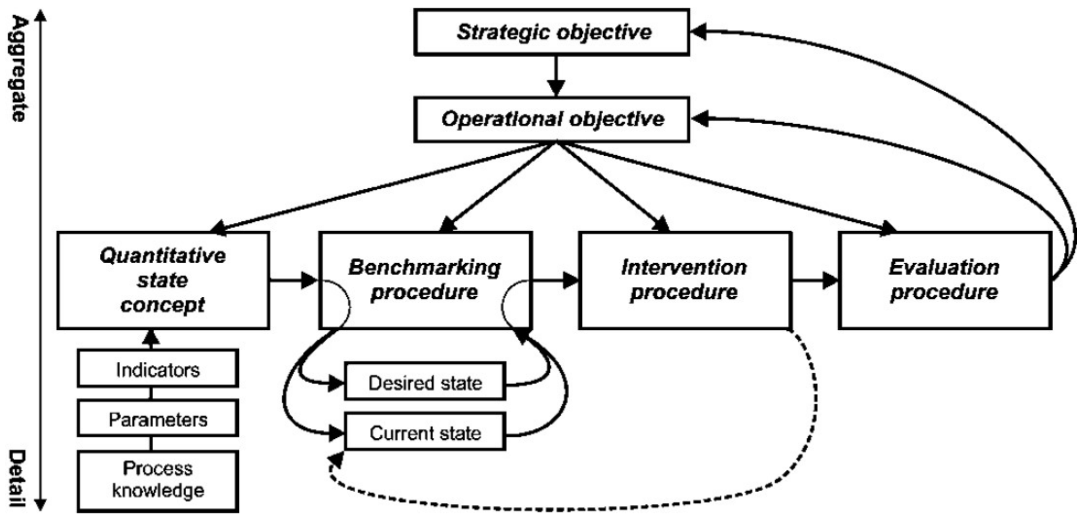


Figure 2.3: A 'basic' Frame of references. Source: (van Koningsveld & Mulder, 2004)

Defining the vision
The vision is to develop ports in the most sustainable way. The ports should be safe, efficient and sustainable to create value for costumers and the highest livability for the population.

Defining the strategic objectives
Strategic objectives should be in line with the vision on quay wall development. The vision can be defined as follows: 'sustainable development of port infrastructure'. The fourteen aspects of sustainability found in sub Paragraph 2.2.3 form the base of the strategic objectives.

Defining the operational objectives
The operational objectives should be in line with the related strategic objective. There are usually referred as targets. Per strategic objective multiple operational objectives are possible. They are straightforward on what should been done to achieve the strategic objective.

Quantitative state concept
The quantitative state concept tries to describe the state of the system in reliable forms. Knowledge of the system is needed to consider a measurable approach. This is because decisions are required to understand how a change in the environmental characteristics can effect a receptor and what tools can be used to measure the extent of the change and the level of response. This is used to quantify whether an action has the desired effect.

Benchmarking procedure
The benchmark procedure makes it possible to systematically and objectively determine if intervention is needed or not. The benchmark procedure consists of two states, namely the current state and the desired state. If the current state exceeds the desired state's threshold, intervention is needed. Desired states normally are derived from trends or legislation.

Intervention procedure
In the intervention method, possible solutions are considered that will reduce the differences between the desired state and the current state.

Evaluation procedure
The evaluation should take place in the development stage of the measure as well as some period after the application (actual effect). The question would be if the operational objective is achieved or not. If it is, the strategic objective should be evaluated as well. This could trigger changes in the objectives.

2.3.2. A framework based on the FoR method to assess sustainability for port infrastructure assets
The following step is to create a framework based on the FoR method that can be used to assess sustainability of port infrastructure assets. This framework will be called the Framework of Sustainable Port Infrastructure (the FoSPI). It consists of the fourteen sustainability aspects that are generally applicable for all types of port infrastructure assets. Each aspects includes one of more targets (in the FoR method called the operational objectives) that are determined by the company and/or by its location's regulations. Furthermore each target requires its own quantification tool (quantitative state concept), reference base (current state), intervention measures (intervention procedure) and evaluation procedure. They depend on the type of infrastructure asset and the location. If the target(s) is (are) achieved, this would mean that the aspect is sustainable. All fourteen aspects should meet their target(s) to conclude that the infrastructure is sustainable. Figure 2.4 visualises the FoSPI.

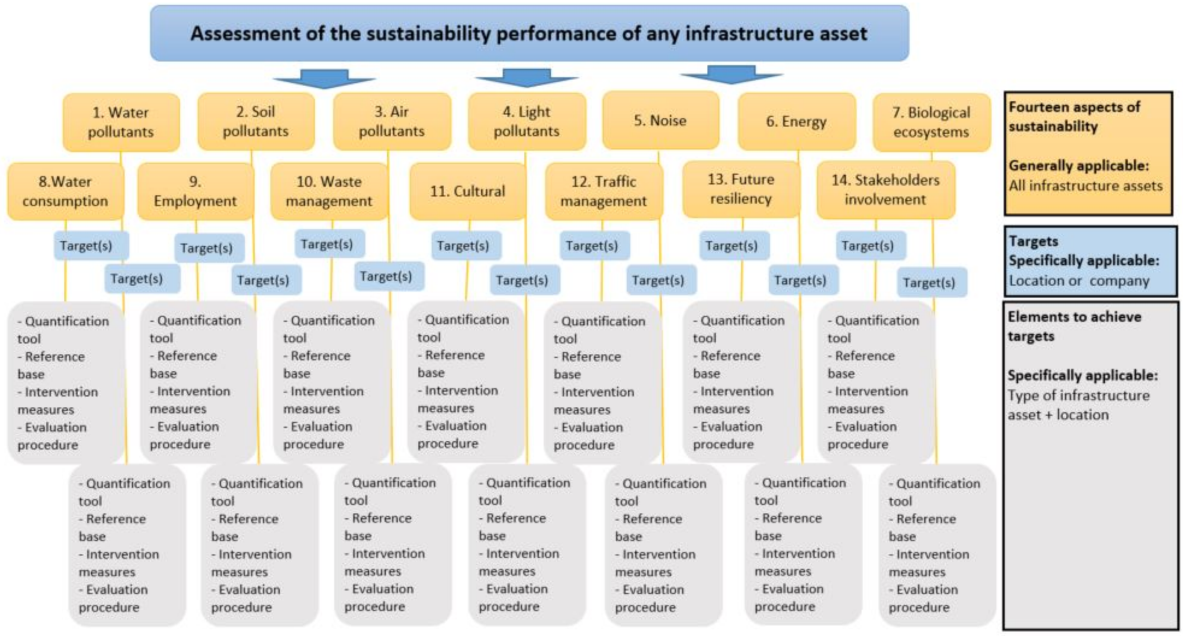


Figure 2.4: The blank Framework of Sustainable Port Infrastructure (FoSPI), based on the Frame of Reference method.

2.4. Applying quay wall development in the PoR to the FoSPI

2.4.1. Different designs of quay walls

Various quay wall designs can be seen around the world. The type of quay wall depends on the local boundaries, (shipping) requirements, cost of materials and durability. In general, three basic designs can be identified: gravity walls, retaining walls and open deck structures. These types can be further specified into more detailed designs. Figure 2.5 visualizes the types of quay walls. Retaining walls are especially constructed for terminals with a large draught. They are soil retaining structures that penetrate below the dredging line which makes it able to obtain their soil retaining function and stability. For additional stability, anchorages must be placed. Currently, the anchored combiwall (for short sea berths) and combiwall with relieving platform (for deep sea quays) are the standardized quay wall designs in the PoR. These quay wall designs are depicted in Figure 2.6.

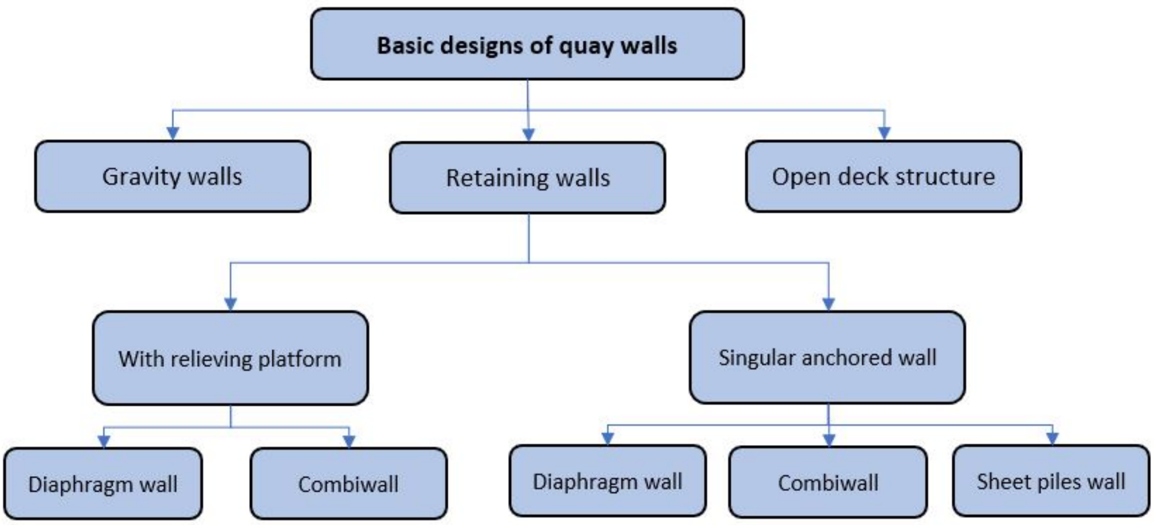
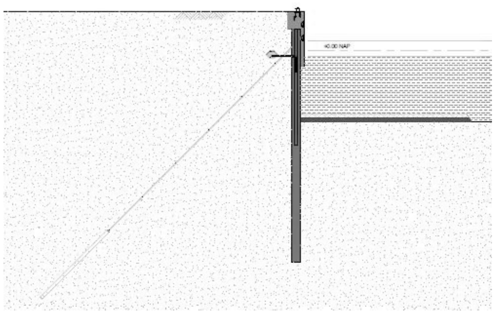
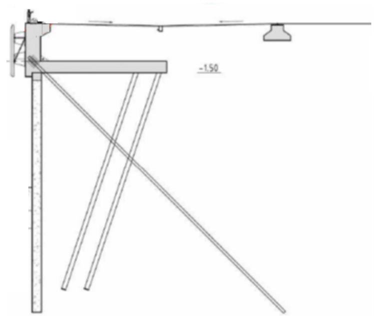


Figure 2.5: The basic designs of quay wall structures



(a) An example of an anchored combiwall



(b) An example of a diaphragm wall with a relieving platform

Figure 2.6: Two examples of basic quay wall designs. Source: PoR internal report, (De Gijt & Douairi, 2013)

2.4.2. Results of the FoSPI

The FoSPI is completed for quay wall projects in the PoR. The underlying FoR method is an iterative method that consists of input of various stakeholders. Discussing and iterative determining all fourteen aspects of sustainability including the input of stakeholders would take a considerably period of time. It is chosen to make an initial determination.

The initial determination is made using literature sources. If an element of the method can not be determined, this means that the author didn't find a reliable source to describe the element or to verify the statement. At the end of each aspect, a conclusion is made that indicates which elements of the aspect are defined and which ones are not. This is indicated with different colors. The color green signifies that the concerned element is defined by a reliable source. The yellow color indicates that the element is defined, although the definition raised questions by the author. The reasoning why will be described as well. The color red signifies that the element is not defined by a reliable source. As example, the sustainability aspect 'Air pollutants' will be resolved below. The other aspects can be found in Appendix B.

Aspect of sustainability 1: Air pollutants

Strategic objective	Source
To achieve levels of air quality that do not result in unacceptable impacts on, and risks to, human health and the environment.	(European Environment Agency, 2017)

According to the European Environment Agency's web page (European Environment Agency, 2017), a quality level that does not result in unacceptable impacts on, and risks to, human health and the environment, is wanted. This is the strategic objective related to air pollution. Air pollutants can be divided in the following gases: greenhouse gases (GHG), toxic gases that create health problems to the local community, and remaining non-toxic gases that create health problems. In this example, the toxic gases will be elaborated further. The other gases are described in Appendix B. Toxic emissions are regulated in Europe by maximum allowed concentrations. The following toxic gases are defined: sulphur dioxide (SO_2), nitrogen oxides (NO_2), particle matters (PM10 and PM2,5), carbon oxide (CO), lead, benzene, ozone, arsenic, cadmium, nickel and benzopyrene. Scientific evidence shows that some of these components (i.e. arsenic, cadmium, nickel) have no identifiable threshold below which these components do not create health risks (E.P. & C.o.E, 2015). Minimizing the emission of those components should be the goal. In this objective, the aim is to quantify the following main air pollutants in construction and navigation projects: particle matters (PM10), sulphur dioxide (SO_2) and nitrogen oxides (NO_2). The other gases are not considered further due their minor emission in construction and navigation (according to Font et al. (2014), Lonati, Cernuschi, and Sidi (2010)) and Port of Rotterdam (2014)).

For this example, only one operational objective (target) will be further elaborated. This is the emission of sulphur dioxide.

Operational objective: Sulphur dioxide

Operational objective	Source
The concentration of sulphur dioxide (SO_2) should be below 20 μg/m^3 for 24-hour mean, 350 μg/m^3 for hour mean and 500 μg/m^3 for 10-minute mean . In general, the emission should be reduced with 28 % in 2020 compared to 2005.	(World Health Organization, 2006), (Ministerie van Binnenlandse Zaken en Koninkrijksrelaties, 2019) and (E.P. & C.o.E., 2016)

Sulphur dioxide is a gas that is released during the combustion of fossil fuel. Higher concentrations of SO_2 could cause respiratory complaints to people with asthma or chronicle lung diseases. In addition, sulphur dioxide causes acidification and eutrophication.

Quantitative state concept:
Sulphur dioxide is a combustion gas that is emitted through engines. Specific key values of SO_2 can be used to quantify the expected emission. However, if the total emission of SO_2 should be reduced, the LCA method is required. This is not possible with the specific key values. Another quantification tool is not identified yet.

Benchmarking procedure:
The current situation can be determined using the key values from LCA. At the moment, the emission of sulphur dioxide is determined for specific projects, however the general emission of a quay wall is not.

The desired situations can be separated into two parts. One is the desired goal to stay below the maximum concentration that is harmful for the environment. This is short term and can be seen per project. It is calculated beforehand. The World Health Organization set the guideline at 20 μg/m^3 for 24-hour mean and 500 μg/m^3 for 10-minute mean (World Health Organization, 2006). The Port of Rotterdam has to adhere to the 'Wet milieubeheer'. In chapter 5, title 5.2 'Luchtkwaliteiteisen' the quality criteria of air emission in the Netherlands is addressed. This law of 2017 is known as 'Wet luchtkwaliteit' (Wlk) (Ministerie van Binnenlandse Zaken en Koninkrijksrelaties, 2019). For sulphur dioxide regulations, the maximum concentrations can be found in Table B.1. When applying the most strict guideline, this would mean that the concentration of SO_2 should be below 20 μg/m^3 for 24-hour mean, 125 μg/m^3 for hour mean and 500 μg/m^3 for 10-minute mean.

Table 2.1: Dutch regulation on sulphur dioxide

Time	**Concentration [$\frac{\mu g}{m^3}$]**
Day average concentration, max 3 times a year exceeded	125
Hour average concentration, max 24 times a year exceeded	350

The second desired goal is the emission reduction on the long term. Under the revised protocol, the EU is set to reduce its SO_2 emission for 2020 with 28 % compared to 2005 (E.P. & C.o.E., 2016). However the reference state of 2005 is not known.

Intervention procedure:
Possible intervention measures are the electrification of machinery, usage of different fuels and usage of after-treatment installations like scrubbers. For the maximum allowed concentration levels, an additional possible intervention could be to optimize the construction schedule. However, the impact of these measures are not known. More research is advised.

Evaluation
The concentration of SO_2 should be below 20 μg/m^3 for 24-hour mean, 125 μg/m^3 for hour mean and 500 μg/m^3 for 10-minute mean. This is calculated beforehand to not cross these limits. In practice, the actual levels are not measured. In addition, a solution how to account the emission is not found yet.

<u>Results</u>
Figure 2.7 shows the elements of the Frame of Reference and their related colors. The strategic and operational objective are identified by a reliable source and indicated in green. The quantitative state concept, current state, desired state and intervention procedure are indicated in yellow. This is due to a missing quantification tool based on the LCA method, a missing current quantified quay wall, a missing 2005 reference base and a missing quantification of the intervention measures. The evaluation procedure is not identified yet and indicated in red.

Sustainability aspect		Strategic objective	Operational objective	Quantitative state concept	Benchmark procedure		Intervention	Evaluation
					Current state	Desired state		
Air pollutants	1.2 Sulphur dioxide							

Figure 2.7: Results of operational objective 1.2: Sulphur dioxide, in aspect of sustainability: Air pollutants

Results of all aspects of sustainability

The previous result is for one operational objective from one strategic objective. All the remaining fourteen aspects of sustainability (hence the fourteen strategical objectives) are solved in Appendix B. The total results are shown in Figure 2.8.

Sustainability aspect		Strategic objective	Operational objective	Quantitative state concept	Benchmark procedure		Intervention	Evaluation
					Current state	Desired state		
Air pollutants	1.1 Greenhouse gases							
	1.2 Sulphur dioxide							
	1.3 Nitrogen oxides							
	1.4 Particle matter							
	1.5 Odor							
Water pollutants	2.1 Water turbidity							
	2.2 Contaminants							
Soil pollutants	3.1 Contaminants							
Water consumption	4.1 Fresh water							
Noise	5.1 Airborne noise							
	5.2 Underwater noise							
Waste management	6.1 Circularity							
Energy	7.1 Renewable							
Light pollution	8.1 Light							
Biological ecosystem	9.1 Ecosystems							
Employment	10.1 Safety							
Cultural	11.1 Archaeology							
Future resilience	12.1 Floods							
	12.2 Adaptability							
Traffic management	13.1 Resiliency							
	13.2 Hindrance							
Stakeholder involvement	14.1 Stakeholders							

Figure 2.8: Results of the FoSPI applied to quay wall development in the PoR

From Figure 2.8 it is found that only four out of fourteen aspects could be specified to be further assessed. The other aspects are not able to be specified as the quantification tool, current state, intervention measures and/or evaluation procedure are missing. To assess the quay wall in total, the remaining eleven aspects should be defined and investigated further. It can be concluded that it is not possible to assess a quay wall at the moment using the FoSPI.

The research will focus on one PoR prioritized non-defined aspect. This is determined using literature and interviews with PoR personnel. This will be further elaborated in Chapter 3. For this aspect, the quantification tool, a reference state, intervention measures and an evaluation procedure for quay wall specifically are not defined yet.

3

The prioritized aspects of the PoR and the specification of the FoR elements.

3.1. Introduction of the prioritized sustainability aspects in the PoR

In Chapter 2, the applied FoSPI for quay wall development in the PoR showed that four aspects were specified and can be further assessed, and eleven that were not. In this Chapter, one prioritized aspect (or one target) of the PoR is further elaborated. First, the mission and vision of the PoR and an Insight report of 2017 are analyzed to obtain the PoR's sustainability focus. The statements from the analyzed documents are described in sub-Paragraph 3.2. Furthermore, interviews are conducted with four PoR employees from different divisions and they are asked to give their opinion on sustainable quay wall development. From the obtained information, it can be concluded which sustainability aspects are prioritized. Next, in Paragraph 3.3 the level of specification of the prioritized aspects for the PoR is discussed.

3.2. Prioritized in the PoR

3.2.1. Mission and vision of the PoR

The current mission and vision of the Port of Rotterdam are shown below (Port of Rotterdam, 2019b).

- **Mission:**

  The Port of Rotterdam Authority creates economic and social value by working with costumers and stakeholders to achieve **sustainable** growth in the world-class port.

- **Vision:**

  We continually improve the Port of Rotterdam to make it the **safest**, most **efficient** and most **sustainable** port in the world. We create value for our customers by developing logistics chains, networks and clusters, in both Europe and growth markets worldwide. As an enterprising port developer, the Port Authority is the partner for world-class clients. In this way, we are also strengthening the competitive position of the Netherlands.

From the sustainability web page of the Port of Rotterdam (Port of Rotterdam, 2019c), the following quote on sustainability can be found.

'*We are committed to ensuring that the port and its environs are **safe, healthy and appealing**. We aim to counter **climate change** while ensuring that the port area makes a significant contribution to Dutch prosperity and **employment**. We are challenging our own organisation. And we are inviting **stakeholders** in and around the port to collaborate on the challenges we encounter in developing the port. Together we will create **economic and social value and realise sustainable growth***'.

From the Insight Report of 2017 (Port of Rotterdam Insight, 2017), the following statement of Remco Neumann, PoR Authority's Corporate Social Responsibility program manager can be found:

"*It's realistic to expect that industry and logistics will be virtually – or by that time, even entirely –* ***zero-emission and silent****. We presently recognise that growth in the industrial era has had a number of undesirable side effects. In* ***2050****, there will be* ***no more noise pollution or air pollution and no negative environmental impact.*** *There's a growing awareness that it is necessary, and indeed possible, to make this transition. "..."This sustainable society is going to happen anyway, so you can better become an active part of the transition.*"

According to the statements, the mission is to achieve sustainable growth in terms of safety and employment, health (noise and air pollution), climate change, stakeholder participation and remaining pollutants (no negative environmental impact).

3.2.2. Interviews with PoR personnel

Four interviews were conducted with Port of Rotterdam personnel. A Senior of Port Development, a Senior Environmental Management, a Senior of General Management and a Senior of Finance. The interviewees were asked to fill in a list with the most important aspects of sustainability and the rate the importance for sustainability on a scale of 1 to 3. A value of 1 is a low focus and three is a high focus. Note that not all the descriptive terms used in the interviews correspond with the sustainability topics described in Chapter 2. This is because the terms used in the interview where the old terms, which were re-described later on. In Appendix C.1, the questionnaires and the list of change in descriptions are given.

From these interviewees, the aspects were given a score and the average was calculated. The most prioritized aspects were defined as the aspects which score is higher than the average total score (average score of 2.10). The following aspects are considered important by the four interviewees:

Water pollutants (= 2.25)	Noise (= 2.75)	Waste management (= 2.50)
Soil pollutants (= 2.25)	Biological ecosystems (= 2.38)	
Air pollutants (=2.25-2.75)	Employment safety (= 2.75)	

Note that in this interview, the focus was specifically on quay wall development. The aspects with a low score can be prioritized by the PoR when the focus is not specific for quay wall development.

3.2.3. Results of the prioritized aspect

The pollutants (air, water, soil and noise), safety of employment and biodiversity are mentioned, both in the reports and web pages (Port of Rotterdam, 2019a), (Port of Rotterdam, 2019b) and (Port of Rotterdam, 2019c) and in the interviews. In consideration with these results, the results of the applied FoSPI (see Figure 2.8) and the PoR personnel, the author chose to consider GHG (target in the aspect air pollutants) as most prioritized. The other prioritized aspects are considered important, but only GHG emission in quay wall development is further looked into, which is further specified in the following Paragraph.

3.3. The level of specification of the FoR on GHG emission in the PoR

3.3.1. Specified elements of the Frame of Reference on GHG emission

The strategic objective

According to the FoR method, the first element is the strategic objective. This can be found in statements of the PoR. It states that in 2050, there is no air pollution (Port of Rotterdam Insight, 2017).

The operational objective (target)

In 2018 the Port Industrial Cluster was responsible for approximately 20% of the total green house gases (GHG) emission of the Netherlands (Gerretsen, 2018). In Report 'Duurzame aanpak' (Port of Rotterdam, 2019a) which focuses on the sustainability of PoR infrastructure projects specifically, agreed targets and ambitions in port development and asset management are described. The following are related to reduction of the GHG emission:

- The PoR has agreed an innovation program for infrastructure to focus on a reduction of 10% carbon emission through innovation and optimization.
- The PoR has the ambition to execute the PoR port projects at least in line with the dutch CO_2 reduction goals (reduction of 49% in 2030 and 95 % in 2050 compared to 1990).

The PoR is following the Paris Climate agreement, although its strives to climate neutrality in 2050. This would mean that the emission of CO_2-eq should be equal to adsorption of CO_2-eq in 2050. In this report, adsorption is not taken into account, hence the emission should be equal to zero. The climate agreement says as well that the emission should be reduced with 49% in 2030 (compared to 1990), this is an operational objective as well by the PoR. The first uncertainty is found here. The reference situation of 1990 is not known, so the target of 49 % in 2030 can not be known. Hence the remaining strategic objective is that the PoR projects are climate neutral in 2050.

The year of 2050 is far away. The port has two option at this point. First one is to do nothing at the moment and let the market do 'its' work. This could be seen as a situation in which the port could look in the year 2048 to their assets and use the tools at that moment to achieve their goal. However the port has an important influence in the process, which can not be neglected. In the conducted interviews by the author with contractors (see Appendix C.2), they both expressed their feelings about how the port should steer in sustainability to persuade the market. As principal of infrastructure projects, the port authority can express particular themes as important and give it a financial stimulant (i.e. E.M.V.I process). The contractors are not going to change on environmental aspects if the client does not ask for it (see Appendix C.2). So the statements and the operational objective indicate that action is needed.

The quantitative state concept

Firstly, the greenhouse gases emission of quay wall development during its full life cycle is sketched and is depicted in Figure 3.1. On the x-axis, the life time in years is used. On the y-axis, the GHG emission is shown. Note that the Figure is a sketch and the quantity of the y-axis is indicative and not a reality. It shows that during the design phase (due to material production) and construction phase, the highest emission is found. During the maintenance phase, emission is very low due to the hardness of the structure. The end-of-life phase shows an increase as well, although it is not as high as the first two phases. The system is now understood, but an objective quantification tool is not determined yet.

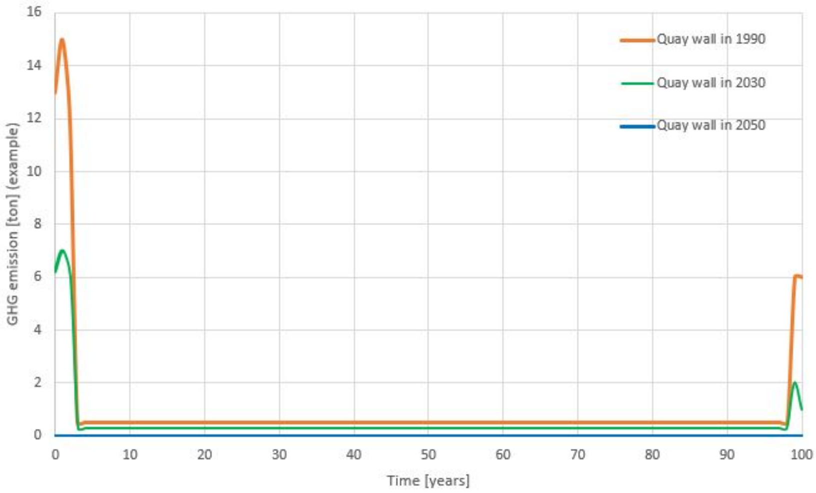


Figure 3.1: An indicative sketch of the emission of GHG in the 100 year life cycle of a quay wall. The emission of GHG is mostly in the production, construction and end-of-life phase.

The desired state

The desired state is the carbon neutrality of PoR infrastructure projects in 2050 according to the PoR statements.

The current state (reference state)

Figure 3.2 shows the emission of GHG in the year 2015/2016. In that year the carbon footprint of the PoR and its cluster is approximately 30 megaton CO_2-equivalences. CO_2-equivalences is a measure unit that includes all GHG. A detailed description can be found in Appendix B.1.1. The pollution of those GHG are compared to carbon pollution and expressed into CO_2- equivalences. Most of that carbon emission is due to the generation and usage of energy by the industrial cluster. The PoR is not directly responsible for the emission and has less influence to intervene with decisive measures to reduce the carbon emission. However the impact on the total carbon emission can be large. The PoR can contribute by promoting sustainable measures for companies. Different programs are set up that include projects like the transition to hydrogen power, biomass and, carbon capture and storage (CCS) (de Graaff & ten Bosch, 2019).

Figure 3.2: Footprint Port of Rotterdam in the year 2015/2016. Source: (Port of Rotterdam, 2019a)

An engineering bureau was hired to achieve an insight of the carbon footprint of the PoR projects (column 2 of Figure 3.2). The scope was to know the volume of the yearly carbon emissions of construction, management and maintenance related to the PoR projects. In the annual calculations, the projects of the divisions PoR-Port Development (PoR-PD) and the PoR-Asset Management (PoR-AM) are considered. Hence this is not an assessment for quay walls in particular, but includes all the PoR infrastructure projects. Note that the calculations are made in DuboCalc generally. From mid 2015 until mid 2016, the infrastructure projects in the PoR had an emission of approximately 90 kilo tonnes (kt) CO_2-equivalences (van Haaren, 2017). Though it contributes a small part of the total carbon emission, the PoR is the principal for the projects and it has the authority over these projects. The influence is high although the impact is moderate. From mid 2016 until mid 2017, the infrastructure projects of PoR had an emission of approximately 90 kt CO_2-equivalences (ten Bosch, 2018). From mid 2017 until mid 2018 the emission increased to approximately 180 kt. (based on preliminary data, data under review). This is an increase of approximately 200 %, however the amount of projects decreased to 22 (approx. -50 %). Table 3.1 shows a comparison between the projects of 2015/2016, 2016/2017 and 2017/2018.

Table 3.1: Comparison of projects in 2015/2016, 2016/2017 and 2017/2018. This Table is based on preliminary data, data under review. Source: (Internal report PoR)

Subject	**2015-2016**	**2016-2017**	**2017-2018**	**Change 2015-2016 vs 2016-2017 [%]**	**Change 2016-2017 vs 2017-2018 [%]**
Carbon emission [kt]	90	90	180	approx. cst.	approx. +200
Projects [quantity]	28	41	22	approx. + 45	approx. -50

From Figure 3.3 it can be seen that the dredging work during construction and maintenance causes the highest emission rates in 2015/2016 and 2016/2017, respectively 49 % in 2015/2016, 55 % in 2016/2017 and 37 % in 2017/2018. Dredging work for maintenance purposes is depended of the weather of the specific year. A year with many storms will lead to more sediment in the navigation channels. This will increase the amount of material for dredging.

The soil excavation and backfill is responsible for 6 % in 2015-2016, almost a quarter of the total carbon emission in 2016/2017 (23 %) and was equal to 14 % in 2017/2018. Bed, bank and shore protection increased as well from 2 % to 7 % and decreased again to 3 %. The emission due to steel reduces radically from 20 % to 3 % and a year later on increases again to 23 %. The emission due to concrete reduced from 6 % to 3 % and increased to 17 % in 2017/2018. In conclusion, the results fluctuate considerably.

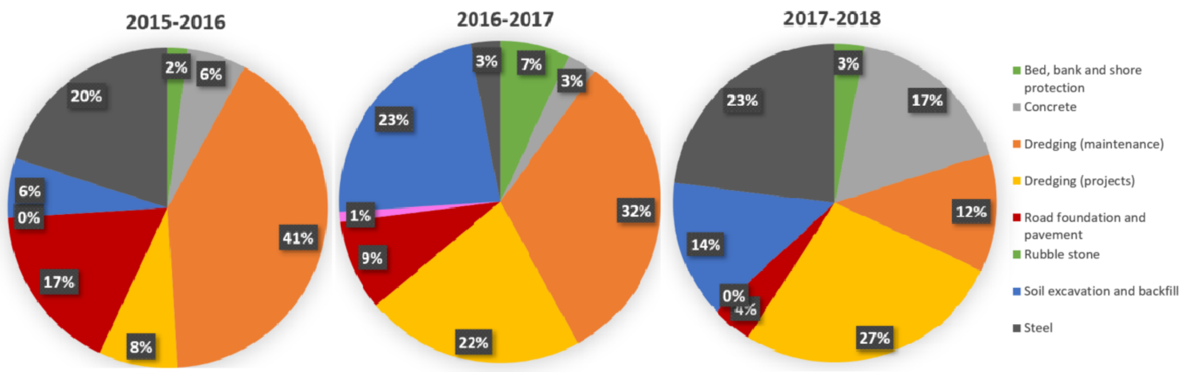


Figure 3.3: Distribution of CO_2 emission per category for the year 2015/2016, the year 2016/2017 and the year 2017/2018. Source: (Port of Rotterdam, 2019a)

The PoR specified the current state as the GHG that are emitted over the years. However the results fluctuate considerably over the years: the yearly quantification of CO_2-eq increases from 90 kt to 180 kt in three years although the amount of projects decreases. This indicates that the types of projects vary, hence their impact vary as well. it depends on in which year certain multiple year projects are assigned, which projects are executed in a year, the different sizes of projects, the variety of natural circumstances and how many projects there are in a year. This makes it challenging to distinguish improvements or deterioration of the situation and makes evaluation complicated. It gives an indication of the GHG emission, but it does not give a coherent result. It is not advised to use this information for the current state as well as for the evaluation procedure.

3.3.2. Unspecified elements of the Frame of Reference on GHG emission.

The quantitative state concept

Secondly in the quantitative state concept, the indicators are defined, however a tool that assesses GHG objectively and is representative for quay wall development is not. This will be further discussed in Chapter 4.

The current state (reference state)

With the present information on GHG emission, the current state (reference state) can not be determined. The GHG emission of a current quay wall project is not known.

The intervention measures

Intervention measures are already proposed although their impact is not quantified. This will be discussed in in Chapter 6.

The evaluation procedure

For the evaluation element, the PoR has at the moment year on year greenhouse gases emission data for all the PoR projects. For evaluation reasons, year on year numbers give an indication of the GHG emission, but does not give a coherent result. Depending on the year, a large variation of projects and related emissions can be expected. This depends on in which year certain multiple year projects are assigned, which projects are executed in a year, the different sizes of projects, the variety of natural circumstances and how many projects there are in a year. Results will not give an indication on how much kt GHG are reduced. Another approach should be used here and this will be discussed in Paragraph 5.1.

3.3.3. Results of the level of specification

The previous sub Paragraphs have showed that the quantification tool, intervention measures and evaluation procedure to achieve the GHG target of the PoR, are not specified yet. In Figure 3.4, the FoR method is depicted in which the specified elements are highlighted. In the next Chapter, a quantification tool is selected. This tool is questioned about its ability to quantify GHG, its objectivity and its representation to quay wall development.

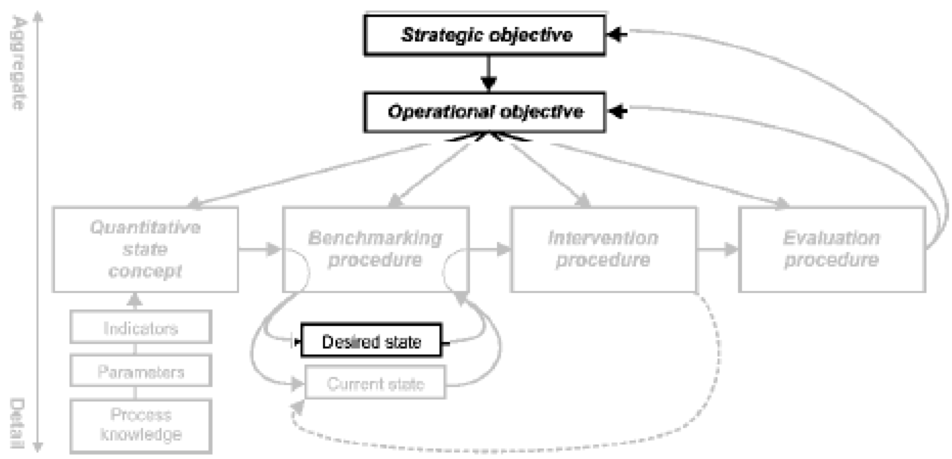


Figure 3.4: The basic Frame of Reference in which the specified elements are highlighted. Based on source: (van Koningsveld & Mulder, 2004)

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4

Determining the quantification tool

4.1. Introduction of the possible quantification tool

According to the FoR method, the quantitative state concept element needs a calculation tool to quantify the GHG. A common way to quantify the emission of GHG during the life cycle of infrastructure projects is to use life cycle assessments (LCA) of the materials that are used and actions that are executed by the constructors and producers. In Paragraph 4.2, the different LCA databases will be described. In Paragraph 4.3, different calculation tools are considered that quantify GHG and the most appropriate one is considered. The chosen calculation software is assessed on the ability to quantify GHG, the objectivity and the representation of the tool on actual quay wall development in Paragraph 4.4. In Paragraph 4.5 the representation of the tool on actual quay wall development is discussed.

4.2. LCA databases

The fundamental data for LCA on GHG is provided by various databases. These databases are established by certain companies. Two wide-range used databases are Ecoinvent and USLCI. Ecoinvent is a global database where as USLCI is focused on the United States of America's territory. Ecoinvent is a well used and generally accepted database (Wernet et al., 2016). Ecoinvent's data can be extrapolated to multiple regions in the world to increase the relevancy. For that reason it is usable for assessment of infrastructure projects in Europe. Ecoinvent contains industrial life cycle inventory data on energy supply, resource extraction, material supply, chemicals, metals, agriculture, waste management services, and transport services (Wernet et al., 2016). Producers of materials publish their LCA data in the database of Ecoinvent and they receive technical support during the data sets creation, submission and the external review. As a result, the database is completed with different materials that estimate the LCA values for specific products.

The Nationale Milieu Database (NMD) is a Dutch database developed to provide an unambiguously calculation method to assess sustainability of infrastructure, utility and construction projects. It is controlled by Stichting Bouwkaliteit (SBK). This database is used in various tools. One of the sources of the NMD is the Ecoinvent database. Producers can also provide their product information which will be published in the database. The advantage for the producers is that their products are found in the different tools. For a producers to publish its product in the database, a Environmental Product Declaration (EPD) should be obtained (Scholtes & Haas, 2015). The database can be consulted in charge of a paid membership. In the NMD, three categories are defined:

- Category 1 data: data is related to the brand and the product is assessed by a third party according to the SBK-assessment protocol.
- Category 2 data: data is not related to a brand and the product is assessed by a third party according to the SBK-assessment protocol.
- Category 3 data: data is not related to a brand and the product is not assessed according to the SBK-assessment protocol.

4.3. Quantification tools

To simplify the LCA assessment, various programs are available. Some programs are specially for advanced users as some are simplified programs for a more averaged crowd. SimaPro is a leading software tools used for life cycle assessments and an advanced program. This will be explained below. Secondly, a sector specific simplified software, called DuboCalc, will be looked into.

4.3.1. SimaPro

SimaPro is a product modeling and assessment software and runs on Ecoinvent data (Herrmann & Moltesen, 2015). It is the leading software tools used for life cycle assessments. In this advanced programs, the different data should be connected by the constructor him/her-self. As an example: if a steel pile is assessed, the constructor should determine the mass of the pile and the related actions and characteristics per pile (i.e. machinery, transport distance, recycling percentages, failure percentages). Greenhouse gases can be determined with this tool. An advantage of this program is that with enough expertise, the objects can be made with a high accuracy. However, creating this all by hand, could cause a significant increase in administration work and financial costs.

4.3.2. DuboCalc

DuboCalc is a calculating program, developed by Rijkswaterstaat in cooperation with the Dutch government, which makes it possible to express the environmental impact of a product into an economical value. It can contribute to achieving the sustainable ambitions (Ministerie van Infrastructuur en Milieu, 2016). The software is simplified and made sector specific. It consists of pre-designed objects. DuboCalc is based on the Life Cycle Assessment (LCA) method and is used in infrastructure, construction and utility projects . At the moment, the program is maintained by Royal HaskoningDHV (technical consultant) and Cenosco (IT company). DuboCalc calculates environmental effects of material and energy usage over their total lifespan, from the material source to the destruction. Table 4.1 shows an overview of different environmental effects.

The program uses data from the NMD. For specific infrastructure objects, all the different data to describe such an object is collected. These parameters are expressed in their related unit. Consequently, a research based price per unit is taken into account. As a result, this gives a total value. All the results are expressed in euros and are called the Environmental Costs Indicator ('Milieu Kosten Indicator' or MKI). The higher the MKI value is, the higher impact the material or object has on the environment. When the outcomes are compared, it will give a straightforward overview of the pollution of each alternative individually. Construction companies can use DuboCalc and the results to steer their sustainability strategy. Technical consulting companies can advise purchasing parties to set up sustainability visions and action plans (van Driel, 2017).

Table 4.1: Costs of different environmental effects. Source : (Stichting Bouwkwaliteit, 2019)

Environmental effect category	**Equivalent value**	**Costs [€/kg]**	**Source**
Humane toxicity - HTP	1.4-DCB eq	0.09	TNO
Fresh water aquatic ecotoxicity - FAETP	1.4-DCB eq	0.03	TNO
Marine aquatic ecotoxicity - MAETP	1.4-DCB eq	0.0001	TNO
Terrestric ecotoxicity - TETP	1.4-DCB eq	0.06	TNO
Depletion abiotic raw material - ADP	Sb eq	0.16	TNO
Depletion fossil energy - ADP	Sb eq[8]	0.16	TNO
Climate change - GWP 100. y	CO_2 eq	0.05	CE Delft
Photochemical oxidant creation - POCP	C_2H_2 eq	2.00	CE Delft
Acidification - AP	SO_2 eq	4.00	CE Delft
Eutrophication - EP	PO_4 eq	9.00	CE Delft
Degradation of ozone layer - ODP	CFK-11 eq	30.00	CE Delft

Greenhouse gases are taken into account in DuboCalc. From the results of a calculation, the carbon footprint and related costs can be isolated and used. In DuboCalc, the three categories as explained in sub Paragraph 4.2 are integrated. In addition, a fine linked to the categories is included related to the reliability of the data. Category one and two are desired, because the product data is assessed by a third company according to the SBK-assessment protocol and considered more reliable. That's why these categories have a 0 % additional fine.

Category three is not assessed by a third company according to the SBK-assessment protocol and has a 30% additional fine.

Note that in the current emission regulations for constructions, additional attention goes to the emission of nitrogen oxides (NO_x) and ammonia (NH_3). Although they are not a equivalent value in DuboCalc, they are represented in the acidification category with an equivalence factor. The equivalent value of acidification is SO_2-eq. According to NEN (2013), 1 kg of NO_x is equal to 0.56 kg of SO_2-eq and 1 kg of NH_3 is equal to 2.45 kg SO_2.

Table D.1 shows the advantages and disadvantages of DuboCalc that are found in literature and been discussed during the interviews. According to own observation, a disadvantage is found as well which will be supported in Paragraph 4.6. In Appendix D.1, the advantages and disadvantages are further elaborated.

Table 4.2: Table with the advantages and disadvantages of DuboCalc

Advantage	Source	Disadvantage	Source
The tool reduces the time to make CO_2 calculations by offering various infrastructure objects.	(de Vos, 2016), (van Driel, 2017)	The database behind DuboCalc does not cover the full spectrum of infrastructure objects	(de Vos, 2016), conducted interviews (Appendix C.2)
The tool prevent excessive administration compared to individual LCA's.	(de Vos, 2016)	Circularity is hard to include and causes findings that are contradicting with common sense.	(de Vos, 2016)
Relative simpleness of working with the tool.	(Duurzaam GWW, 2019)	Fixed values for transport distances.	(de Vos, 2016), conducted interviews (Appendix C.2)
		Knowledge about quay wall is required	own observation

4.3.3. Results of the quantification tools

For the assessment of GHG, a specific LCA per object would be the most precise method. This could be done with SimaPro. However, this would mean that LCA of every object used in a development of the quay wall should be determined according to the SBK-assessment protocol by a third party. In practice, this type of assessment will cause excessive administration work, time and financial costs. This would be an obstacle to assess greenhouse gasses. For these reasons, DuboCalc was created to have a standard database to reduce the work. DuboCalc will give an indication of the emitted CO_2-eq. Due to the use of categories and the additional fines, the calculated amount of CO2 emitted is maximised. DuboCalc can quantify the amount of emission and is elaborated further in Paragraph 4.4.

4.4. The objectivity of DuboCalc - Research

4.4.1. Hypothesis

Paragraph 4.3 concluded that DuboCalc has the ability to quantify CO_2-eq. However, the variation of the results when the tool is used by different experts, is not known yet. The tool consists of different objects that can be selected. If the correct objects are not available in the tool, the experts have to make assumptions. These human assumptions may influence the objectivity of the results. To examine what the influence is of the human assumptions, four technical consultants were asked to perform a DuboCalc calculation. This will be further explained in sub Paragraph 4.4.2. To prove that the results show objectivity, a hypothesis is set-up. The desired objectivity from this research can be seen as the reproducibility of the results. Reproducibility is defined as running the same software on the same input data and obtaining the same results (Rougier et al., 2017). Hence there is no difference between the mean and the individual variables. This is called the null hypothesis. The following hypothesis is set-up:

The tool can be called objective if the results show no variation with the mean.

If this hypothesis is not met, it can be said that the tool is not reproducible, hence not objective. If variation occurs, then what is the order of magnitude of the bias? Furthermore, which recommendations can be made to decrease this variation. These questions will be answered in this Paragraph.

4.4.2. Method

Four technical consultants specialized in working with DuboCalc, were asked to perform a DuboCalc calculation to quantify the CO_2-eq emitted during the life time of a quay wall. The data is based on the HES Hartel Tank Terminal (HHTT). This terminal will be described in Chapter 5. However, it should be noted that data from the HHTT and the data that is used in this exercise, are not similar. This is because additional information about the HHTT terminal became available after the exercise had been done. This has lead to different results in Chapter 4 and Chapter 5. Nonetheless, this will not have an impact on the results of the objectivity. The assignment for the consultants were made by the author with given input values. Determining the input values is not part of the exercise. Hence the input data is similar to all consultants. The assignment is given in Appendix D.2.

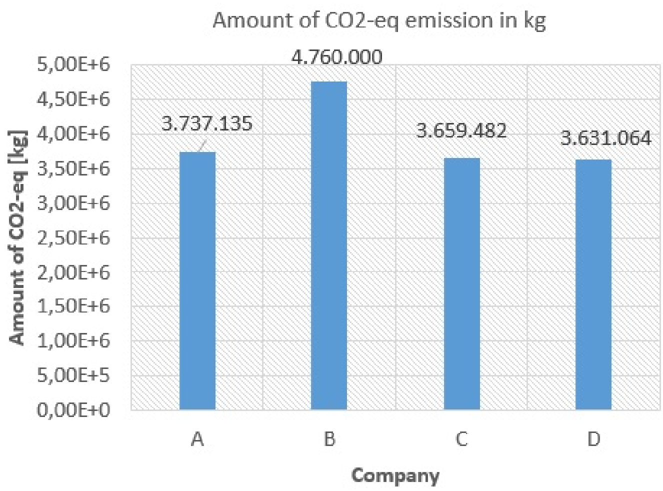
4.4.3. Alterations

The results of company A do not include the Bed, Bank and Shore (BBS) protection (in this case bed protection) and the Impressed Current Cathodic Protection (ICCP). However, from the other companies results, a 100 % resemblance is found for the bed protection and a 67 % resemblance is found for the ICCP. The deviation for the ICCP was expected to be a mistake from one company. After the evaluation with the corresponding company, it was indicated that a copy mistake was made for the ICCP. After a second calculation, a 100 % resemblance was found for the ICCP. With that knowledge, it is assumed that company A has the same results for these two objects. This additional emission is added to the results of company A to have similar input data.

4.4.4. Results

In general

The average value for CO_2-eq emission (n=4) is 3,947 t CO_2-eq. The results vary from 3,737 t with a 5.32 % difference from the average (company A), 4,760 t with a 20.60 % difference from the average (company B), 3,659 t with a 7.28 % difference from the average (company C) and 3,631 t with a 8.00 % difference from the average (company D). Hence the lower limit is equal to 3,631 t and the upper limit is equal to 4,760 t. The percent relative range is 28.60 %. The results shows variation from the average and consequently are not in line with the hypothesis. There is too much variation to call it reproducible. The results will be evaluated per object to determine why the variation occurs. The results are depicted in Figure 4.1



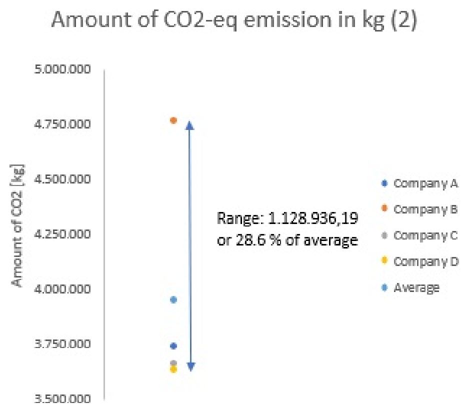


Figure 4.1: The results of the research for the first round. This Figure shows the amount of emitted kg CO_2-eq

Resemblance per object

According to the achieved results, it can be concluded that the answers do not comply with the hypothesis. The following step is to look into the various objects and to see what causes the variation. In Appendix D.4, a translation list can be found of the DuboCalc objects.

The results can be found in Appendix D.3. Figure 4.2 visualizes the matching results per object of a quay wall in percentages. The resemblance is assessed on three topics. The first topic is if the consultants used the same input parameters as described in the questionnaire. The second topic is if the consultants used equal DuboCalc objects to assess the objects from the quay wall. The last topic was if the consultants received the same CO_2-eq results. The resemblance is expressed in percentages. A 100 % score means that all technical consultants did respond the same. If the percentage is 75 %, this means that 3 out of 4 responded the same and consequently 50 % is means 2 out of 4. When 0 % is found, this would mean the all the consultants gave different answers. The questionnaire made it possible to calculate the results first and thereafter to extrapolate to 100 meter quay wall, or to extrapolate the data to 100 m quay wall and thereafter calculate the results. This caused an estimation error. To say that the objects have resemblance, an estimation error 5 % is allowed. Note that the ICCP and bed protection was not included in company A's results and have been neglected in the Figure 4.2.

The first object that is evaluated is the 'Soil backfill'. The input and choice of DuboCalc scores 100 %, although the results does not (75 %). This could be an indication that a mistake was made by the consultant. Looking into the data shows that company A uses a transport distance of 200 kilometers instead of 200 meters. This causes an approx. thirteen times larger result for this object. An estimation error is seen as well of 3%, and is assumed neglectable by the author (< 5%).

Secondly, the 'Soil excavation' shows that the choice of object in DuboCalc is not straightforward. Two out of four experts used the same object, the other experts used different objects. This resulted in a 0 % resemblance of the results. This is due to estimate errors of 8 %, which is assumed not neglectable by the author.

The object 'Temporary sheet piles' has a 75 % resemblance in choice of object and the input is not the same. Company B uses a factor 1.63 to calculate the tonnage, whereas the other companies don't. This causes a different result. In addition, company A has the same input, but the result deviates. The company uses a second object in which they remove the sheet piles wall. This is already included in the first object, as it is a life cycle assessment. These choices will be evaluated.

The object 'Anchorage' causes uncertainty as well. The anchorage exists of grout mortar and anchorage piles. The grout mortar options is chosen by all, but some experts chose a second object, which caused a variety in the input. The anchorage piles were excluded from the research by three companies as they say that there isn't a object that comes close to the real object. One company chose the object 'steel pile small'. Company A chose a different value. This causes that two out of four have the same result.

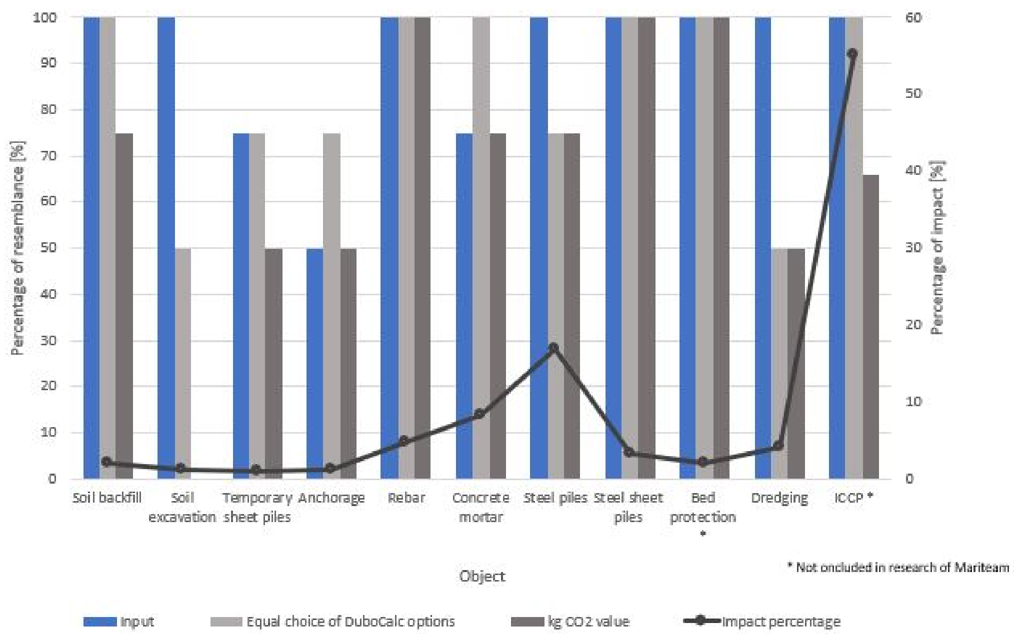


Figure 4.2: An overview of the results of the objectivity research expressed in percentages

The object 'Rebar' shows a 100 % score for all topics.

The object 'Concrete mortar' scores 75 % on the input values whereas company B shows a different value compared to the rest. There is no reason given by the company why it deviates. The selected object is equal to all, resulting in a 75 % resemblance in the CO_2-eq value.

Furthermore for the object 'Piles' the input has a resemblance of 100 %, although the choice of object varies. Company B chooses a different object. In this object, the life cycle of the object is 40 years. The full life cycle of the quay wall is 100 years. This means that DuboCalc will repeat the object 1.5 times resulting in 2.5 times as much steel as needed. This causes a five times higher result than the other companies and in total 1,338 t CO_2-eq is extra emitted. This is 34 % of the average result. Figure 4.3 visualizes the results.

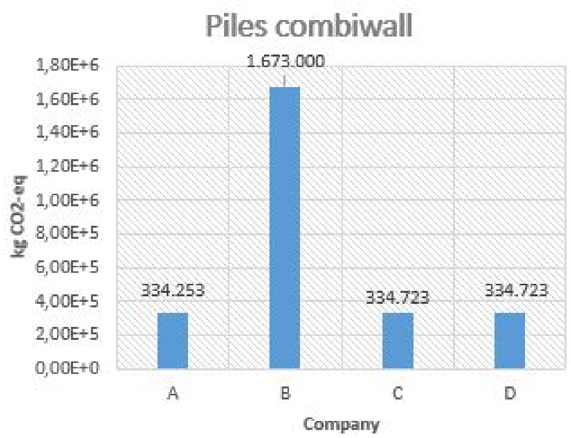


Figure 4.3: Results of kg CO_2-eq of the piles of the combiwall

The object 'Steel sheet piles' shows a 100 % score for all topics.

The object 'Bed protection' shows a 100 % score for all topics. Note that this was not included in company A assessment.

The object 'Dredging' had two given input values. The first possible input was the amount of required dredged material in cubic meters. The second possible input was the amount of Marine Diesel Oil (MDO) in liters. The experts choose the input values and they have a 100 % resemblance with the given input values. However, the choice of object has a 50 % resemblance. The two other companies choose different objects, as this was dependent on the chosen input value. This causes that the results of emitted CO-eq have a 50 % resemblance.

The object 'ICCP' shows a 100 % score for input and choice of object. The result of company B deviates from the other companies, although there is no reason why this should be. This will be evaluated with the company. Note that this was not included in the company A's assessment.

The results do not satisfy the set-up hypothesis. However, the pool of experts is very small, namely n = 4, which could cause a large variation if one company made a mistake. The results of company A, C and D are almost similar, although only three objects have a 100 % resemblance for the caculated CO_2-eq emission. Company B results are an outlier, and when eliminating company B from the results, an average can be found of 3,676 t CO_2-eq emission with a 1.7 % difference of company A, a 0.5 % difference of company C and a 1.2 % difference of company D, resulting in a percent relative range of 2.90 %. This is largely due to large contributors that have a 100 % resemblance. These are the objects 'Rebar' and 'Steel sheet piles'. If company B is excluded in this research, the objects 'Concrete mortar', 'Piles' and 'ICCP' have a 100 % resemblance as well. The object 'Bed protection' is below the 100 t CO_2-eq, the others are above this value. They can be seen as the large contributors of the total assessment. Together they represent approx 85 - 90 % of the total emission. (The object 'Dredging' is above the 100 t CO_2-eq as well, but is not answered equally.) In Figure 4.3, the black line represents the impact per objects in percentages. This corresponds with the right y-axis. Note that the values differ from calculations made in Chapter 5, as already discussed in 4.4.2. In this exercise, it results in an initial determination of the largest emitters.

Company B made a choice that had a large influence on the total assessment, namely the choice of a different object for the steel piles. Secondly, only three objects had a 100 % resemblance for all topics. This is 27 % of the total objects. The results do not comply with the set up hypothesis because the mean is not equal to the variables. It is chosen to evaluate the results with the companies and to see with what reasons some notable assumptions were made.

4.4.5. Evaluation and second results

The companies were interviewed and were asked to give the reasoning behind their assumptions. This explained some different assumptions, but also indicated some mistakes. Table 4.3 shows the assumptions or mistakes behind the choices.

Table 4.3: The assumptions and mistakes made by the companies, including the changes made

Object	Company A	Company B	Company C	Company D
Soil backfill	Mistake: changed the transport distance to 200 meter.	-	-	-
Soil excavation	Mistake: changed the transport distance to 200 meter.	-	Assumption: object 'Making work from work' not applicable as it not said that the removed sand will be used again. Chosen for object 'Soil per axle' because that way the production is not included. Object 'Land sand per axle' with option 'released' could also be used.	Assumption: object 'Work with work: Sand' not applicable as it not said that the removed sand will be recycled. Chosen for object 'Land sand per axle' with option 'Released' because that sand was specifically asked.
Temporary sheet piles	Mistake: removed the object 'Remove temporary sheet piles'	Mistake: factor 1,63 was wrong and removed.	-	-
Anchorage	Mistake: anchorage pile was not taken into account.	Mistake: anchorage pile was not taken into account.	Assumption: Not chosen for a anchorage piles as 1) different piles exist depending on tensile strenght and 2) very small percentage of total.	Assumption: Object 'Steel pile (small)' the closest object to the real anchor piles.
Rebar	-	-	-	-
Concrete mortar C35/C45 CEMIII	-	Mistake: input data was wrong and has been changed.	-	-
Steel piles	-	Mistake: changed object 'Steel pile (large)' to 'Drive pile (steel)'.	Assumption: Object 'Drive pile (steel)' closed to actual object	Assumption: Object 'Drive pile (steel)' closed to actual object
Sheet piles	-	-	-	-
Bed protection	-	-	-	-
Dredging	Mistake: Changed to object 'MDO' as it was more precise for this situation.	-	Assumption: precise for different soil types.	Assumption: Chosen for Suction hopper based on previous assessments.
ICCP	-	Mistake: output data changed	-	-

Company A and company B made some alterations in their calculations. These new results were also analysed resulting in an average value of 3,727 t CO_2-eq emission. Company A has a result of 3,677 t CO_2-eq with a 1.34 % difference from the average , company B has a result of 3,939 t CO_2-eq with a 5.70 % difference from the average, company C has a result of 3,659 t CO_2-eq with a 1.80 % difference from the average and company D has a result of 3,631 t CO_2-eq with a 2.56 % difference from the average. Hence the lower limit is equal to 3,631 t and the upper limit is equal to 3,939 t. The percentage relative range is 8.26 %.

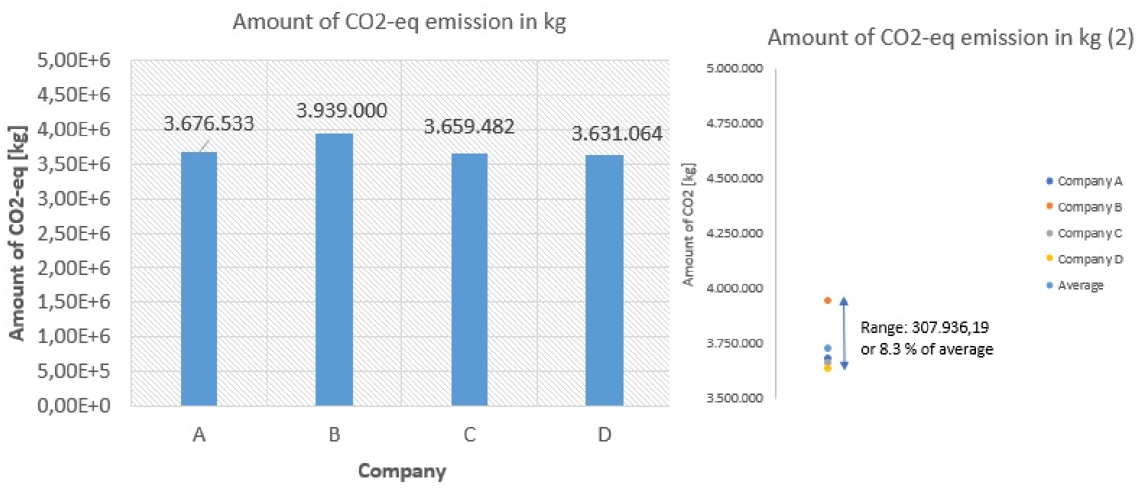


Figure 4.4: The results of the research for the second round. This Figure shows the amount of emitted kg CO_2-eq

Looking at the individual objects, it can be seen that 8 objects show a 100 % resemblance. That is 72.8 % of the total objects. This is an improvement relatively to the previous results. Figure 4.5 visualizes the individual objects. Note that a 5 % error is allowed to be classified as an equal answer when it's due to conversion. The following objects show a difference in the results:

- The object 'Soil excavation' does not deliver matching results. Multiple objects in DuboCalc were possible to use resulting in this variation. Company A and company C use the same input and objects, however do not generate the same results. A possibility is that the error is from conversion, although the difference of approx. 8 % is considered too large.
- The object 'Anchorage' is still considered difficult. The input resemblance has decreased to 0 % and the objects in anchorage still varies. Three companies decided to choose an object for the anchorage piles, but it did not corresponded with each other or the remaining companies. A right object for the piles is not present in the program.
- Finally, the object 'Dredging' increased in object choice and result. Only one company stayed with their decision to not choose the object "MDO".

The results still show a variation, although the range did decreased significantly from 28.60 % to 8.26 %. However it shows that the results do not comply with the hypothesis. The results are not easily reproducible, hence the tool is not sufficiently objective. However the decrease in range shows that when the results are evaluated with the companies, the answers are more in line with each other. The order of magnitude of the application bias is determined to be 8.26 %.

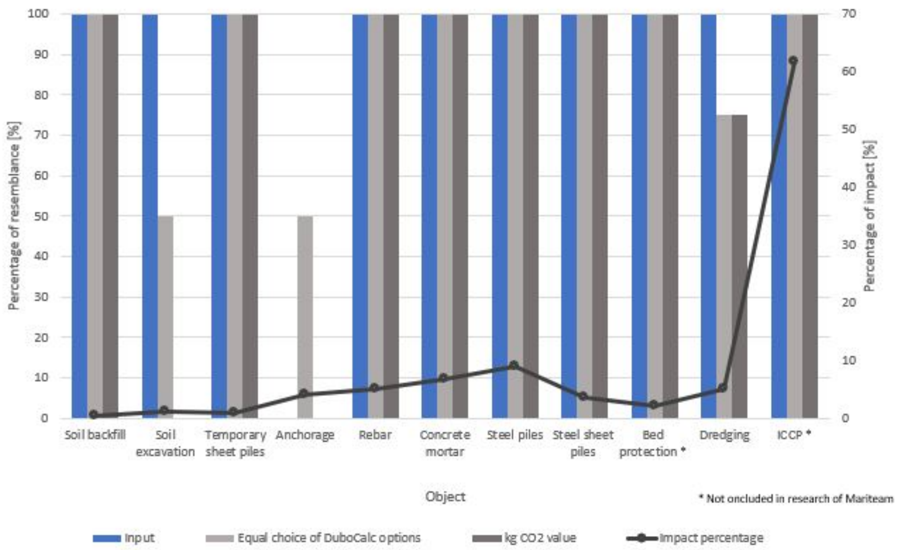


Figure 4.5: An overview of the results of the objectivity research expressed in percentages

4.5. Representation of the reality in quay wall development

Now the ability to quantify and the objectivity of the tool is described, the representation of the results to quay wall development should be considered as well. This is examined by asking the experts about their view, which can be found in Table 4.4. According to the experts it can be concluded that DuboCalc is representative for quay wall development, although some objects are missing in the tool (e.g. anchorage piles) and the correct length or profile of an object is not represented (e.g. steel piles or sheet piles). The experts expect that this will not lead to unacceptable differences although this should be investigated further. For now, the results show that the quantification in DuboCalc sufficiently represents quay wall development although there is room for improvement.

Table 4.4: The representation considered from the experts opinion.

Object	Company A	Company B	Company C	Company D
Representation to quay wall development	Usable but some objects are not representative to the actual situation.	Yes, it is usable. There is room for improvements in time.	Usable to see where changes are possible. More freedom in the ability to change parameters like lifespan and transport distances. Note that assumption and mistake can have influence on the EMVI's. There should be more focus on the notation of the assumptions.	Usable in comparing designs in design phase. The largest contributor are the material extraction and production. More research into what happens if the machinery is representative to the actual situation.

4.6. Results of the quantification tool

The results from previous Paragraphs show that the tool is able to quantify the CO_2-eq and representative enough for quay wall development. However, the objects in DuboCalc are not fully corresponding with quay wall development. Sometimes, multiple objects were possible for one action, leading to different results. This is the case for the soil excavation and the dredging processes. Secondly, certain objects like the anchorage piles were not described in DuboCalc and could not be assessed.

The questionnaire with the exercise for the technical experts resulted in four answers with an average of 3.9 kt CO_2-eq. None of the answers were equal and a percentage relative range of 28.60 % is determined. This does not comply with the null-hypothesis. After a thorough check, discussion and evaluation with the experts, the same exercise was repeated. The experts corrected their mistakes. A new average of 3.7 kt CO_2-eq and a percentage relative range of 8.26 % is determined. In the first result, three out the eleven actions were answered equally, in the second results, this was nine out the eleven actions. It can be concluded that DuboCalc is not entirely reproducible, but can be used after a thorough check, and discussion and evaluation with the experts.

The disadvantages explained in Table D.1 were detected as well. DuboCalc does not cover all objects for quay wall development. This will be a recommendation. Secondly, the mistakes that were made, indicate that in order to use the tool DuboCalc correctly, knowledge is needed about quay wall development. The circularity and fixed values were not directly indicated as a problem in this exercise.

In the following Paragraph, recommendations in terms of improvement of the tool are discussed. In the next Chapter, the tool will be used to quantify a quay wall as reference base.

4.7. Recommendations in terms of tool improvement

Improve the reproducibility

In the first results, a range of 28.60 % was found. After discussion and evaluation of the results, the second results showed a range of 8.26 %. Evaluating and discussing the results with the consultants should be part of process, as it decreases the variation. Secondly, some objects are not represented in the tool. These objects: 'Soil excavation', the anchorage piles 'Anchorage' and the 'Dredging' still cause variation of chosen objects. For object 'Soil excavation' and 'Dredging', there are various applicable objects. The expert is biased i.e. they prefer one object over the other object. The anchorage piles are not represented well, which cause the choice of alternative objects, where others neglect it.

It is recommended to choose a preferred object for 'Soil excavation' and 'Dredging' and make clear to the expert to use that object. Dredging is better quantified using the object 'MDO' and not the amount of dredged material. This is due to the large variety of parameters that can be changed during dredging which influences the amount of fuel. This can be the sailing speed of the ship, the weather conditions, the depth of dredged material etc. It is recommended to use this for further assessments.

For the anchorage piles, a new object should be calculated through a LCA to include this object in the tool.

Improve the representation

Secondly, the experts have made remarks on some objects. This can be found in Table 4.5. It is advised to make new LCA of the large contributors of the results. They all consist of a fine of 30 % (category 3), which implies an uncertainty of the exact quantification. In addition, the input data of ICCP was based on a rapport of RHDHV consultant. However, this is expected to be an oversimplification of the reality. The objects was calculated in DuboCalc as an expression of electricity. The coating (existing of extraordinary materials like titanium) and installation necessary for this are not taken into account as the data is not fully known yet. This is expected to have a considerable influence on the results. This is why a complete LCA is advised.

Table 4.5: Recommendations of the companies

Object	Company A	Company B	Company C	Company D
Soil backfill	-	-	-	-
Soil excavation	-	-	-	-
Temporary sheet piles	-	-	Remark: The tool uses a AZ36 profile where as in reality a PU18 profile is applied. This has impact on the types of used construction machinery and the construction time. This impact should be investigated.	Remark: The tool uses a AZ36 profile where as in reality a PU18 profile is applied. This has impact on the types of used construction machinery and the construction time. This impact should be investigated.
Anchorage	-	-	-	-
Rebar	-	-	-	-
Concrete mortar C35/C45 CEMIII	-	-	-	-
Steel piles	-	-	-	In reality, the length of the piles is higher. This influences the type of machinery and the construction time per pile. This impact should be investigated.
Sheet piles	-	-	Remark: The tool uses a AZ36 profile where as in reality a PU18 profile is applied. This has impact on the types of used construction machinery and the construction time. This impact should be investigated.	Remark: The tool uses a AZ36 profile where as in reality a PU18 profile is applied. This has impact on the types of used construction machinery and the construction time. This impact should be investigated.
Bed protection	-	-	-	-
Dredging	-	-	-	There is no difference made between sludge and sand in the chosen object 'Dredging'. Further research is advised.
ICCP	-	-	-	-

5

Determining the evaluation procedure and the current state

5.1. The evaluation procedure

Following the FoR method, the evaluation procedure element is required to achieve the strategic objective. In Chapter 3, it became clear that evaluation per year is not recommended, due to the different projects of different scales. Another evaluation method is discussed in this Paragraph.

To evaluate the achieved reduction, it is proposed to apply a method that focuses on one specific asset only. In this method, the standard design of an asset, in this case a quay wall, will be assessed. In the PoR, standard designs of quay wall exist for short and deep sea quay walls. The standardized short sea quay wall is an anchored combiwall and the deep sea quay wall is an anchored combiwall with relieving platform. For this research, the 100 meter standard port short sea quay wall is used as the reference base.

The current intervention measures to reduce the emission of this asset need to be examined and will become part of the standard if it satisfy the criteria. This will result in a standard of the asset with the lowest emission possible. This process should be repeated at regular intervals. For this report, a time period of 5 years is assumed. This way, the standard asset will included the lowest GHG emissions possible. This method is theoretical sketched in Figure 5.1. The orange line represents the current situation. If business as usual is assumed, the line will lay between the situation in which no reduction is achieved and the situation where a small reduction is achieved, that is induced due to market trends. The blue line represents the proposed evaluation method. Every step is five years in which interventions measures are applied that further reduces the emission. The target is to reduce to 0 % GHG emission. Note that the Figure is a sketch of what is desired.

In addition, at every interval future technologies should be reviewed to get an insight of what is technical and commercial possible in the next coming decades (see Chapter 6). The current situation of this 100 m standard quay wall will be calculated in Paragraph 5.2.

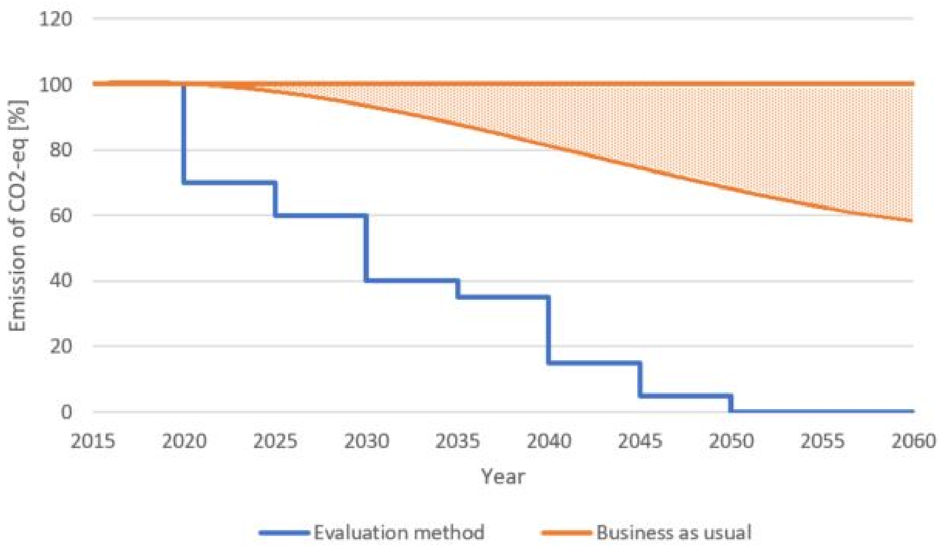


Figure 5.1: The proposed evaluation method. On this Figure the desired standard designs through the years are represented as the blue line. Every step is five years in which intervention measures are applied. The orange line is the Business as usual line, in which the line is likely to decrease due to the market trends.

5.2. Determining the reference base: case study

5.2.1. Introduction of the case study

Following to the FoR method, the current state element needs to be determined. The PoR works with a standard quay wall design. There is a standard short sea quay wall design that is used till NAP -12.0 m and a deep sea design that is used from NAP -16.0m. The case study is an actual quay wall project that is being constructed at the moment in the Port of Rotterdam. This project is the HES Hartel Tank Terminal (HHTT). The standard short sea quay wall is fitted to the actual project. Some changes in the standard quay wall design were made due to the project specific boundaries. However the quantities of materials is quite similar to the standard.

A new tank storage terminal is currently being developed in the Mississippihaven at Maasvlakte 1 in the PoR. The plot covers an area of 27 hectares of land and will provide a tank storage of approximately 1,300,000 m^3. The tenant (HES), will build the secondary port infrastructure and will later on exploit the terminal. The tanks will be suitable for mineral oil products, bio fuels, bulk and ethanol. These products will be imported and exported via sea vessels, barges and pipes. The terminal consists of a deep sea quay wall of 1230 m, a short sea quay wall of 1080 m and a jetty of 317 m. The deep sea quay wall can welcome a VLCC, a Suezmax and a LR2 (Aframax) or a LR2 and 4 MR2 (Handymax). The short sea quay wall consists of the quay wall and a jetty which together provide nine barge berths. Figure 5.2a shows a visualization of the terminal and Figure 5.2b provide the location in the Port of Rotterdam.

(a) Map of the HES Hartel Tank Terminal. Source: PoR

(b) Location of HHTT in the Netherlands. Source: PoR

Figure 5.2: The HHTT terminal location

5.2.2. The short sea quay walls

The short sea terminal consists of a quay wall and a jetty which together can accommodate nine barges. In this terminal, vessels of class between CEMT IV and CEMT VIb are welcome. It has a channel depth of NAP -6.1 m. Figure 5.3 shows a visualization of the short sea berths. In this report, the focus lays on the quay wall development, hence the jetty will be neglected. The full length of the quay wall is 1080 meters over which the profile slightly varies. The south side of the quay wall has a length of 479.94 meters. It is assumed that this side is representative for the profile of the entire short sea quay wall. This side will be discussed in the assessment of the emission of greenhouse gases.

5.2.3. Design of the quay wall

The short sea quay wall belongs to the category of soil retaining structures. The type is a singular anchored wall, in particular a combined wall with anchorage. The lay out is depicted in Figure 5.3. The red line in the Figure visualizes the quay wall, the blue line is the jetty. The area of interest is inside the black box. It has a length of 479.94 meters.

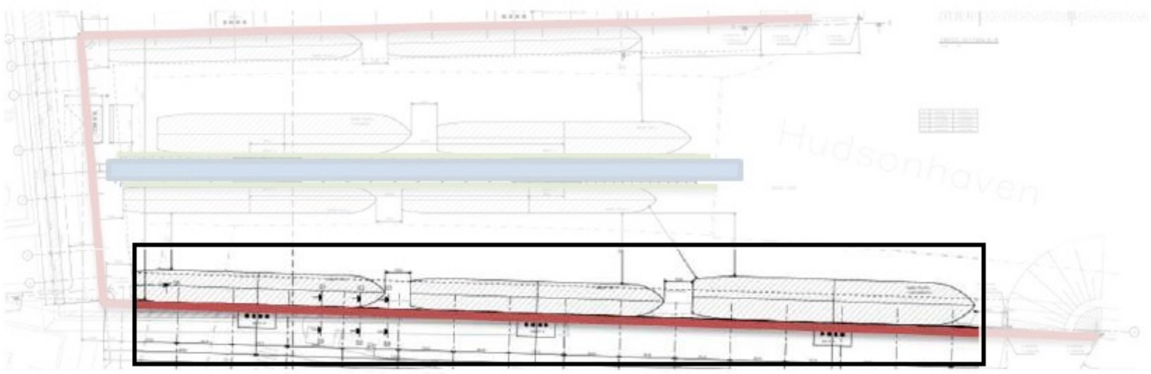


Figure 5.3: The map of the short sea quay wall. The red line is the quay wall, the blue line is the jetty. Inside the black box is the area of interest. It has a length of 479.94 meters. Source: PoR

The quay wall consists of several components. The first component is the superstructure. This design has a capping beam made out of rebar and concrete. This beam has the function of a girder and is able to withstand the loads. In addition, bollards can be placed on it. The second component is the substructure. This is the structure beneath the ground. This quay wall exists of combined steel sheet pile wall system. This means that steel piles are driven into the soil at a fixed distance from each other. Between the piles, standard sheet piles are driven. Interlock openings should be avoided, otherwise it will lose its soil retaining function. The third component are the anchorages that support the soil retaining structure. In this case, the anchors exists of grout anchors and anchor piles. The next component are the breasting equipment. The quay wall has a rigid fendering made out of recycled High Density Polyethylene (RE-HDPE) slabs. The last component are the remaining objects like the quay ladders and the erosion protection of the quay walls. The quay wall will be protected against erosion with an Impressed Current Cathodic Protection (ICCP) system. Figure 5.4 shows the intersection of the short sea quay wall in the HHTT.

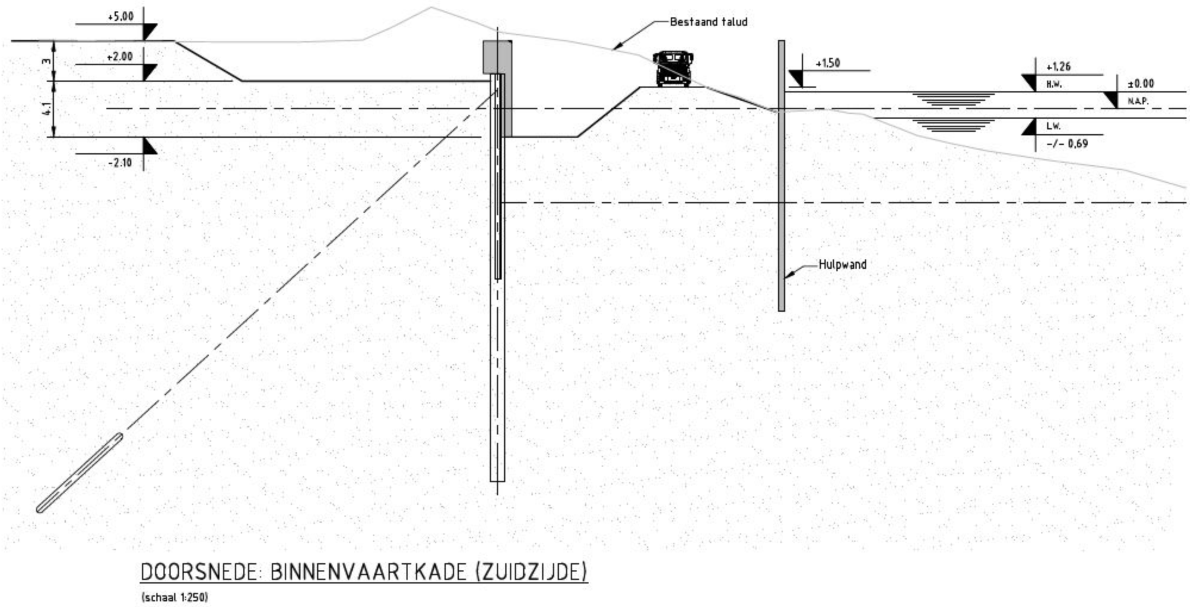


Figure 5.4: The intersection of the south side of the short sea quay wall of HHTT. Source: PoR

For the calculation of the GHG, an inventory of materials is needed. The construction of the quay wall is arranged as follows:

1. Preparation

   In the preparation phase, the required work to make the construction site arranged, is described. This implies the soil improvement, ground work in which soil is excavated or backfilled, the transport of materials and the creation of the construction pit with temporary drainage systems.

2. Structure

   During the construction phase, the different objects are constructed. This implies the combined steel sheet pile wall system, anchorages, the capping beam, bed protection and the remaining objects.

3. Dredging work

   This phase implies the removal of soil in the construction pit to achieve the required draught. This is done by dredging.

The maintenance of the quay wall is also considered and described as follows:

1. Maintenance and management.

   During this phase, the protection of the steel sheet piles of the quay wall is considered. This is done by using an ICCP system.

These phases will be further discussed. The quantity of materials is based on the Inventory List of HHTT and adjusted to the south quay wall. The data of the Inventory List is calculated during the planning of the quay wall and is an estimation.

Preparation

In the preparation phase, 29,900 m^3 of soil is excavated and transported to the nearby Hudson terminal (assumed a distance of 500 meters). The construction site will be supplemented with 9,900 m^3 of sand from the depot (assumed transport distance of 500 meter). A next step in the preparation phase is the placement of temporary sheet piles to construct the pit. Sheet piles PU18 (density of 128.2 kg/m^2) and a length of 10 meters are used over the full length of the quay wall. Temporary drainage pumps systems are required to keep the construction pit dry.

A translation list of the DuboCalc objects to Dutch can be found in Appendix D.4. For the backfill and the excavation of sediments, the option 'Land sand per axle (Released)' and the object 'Ground per axle' is chosen. The placement of the temporary sheet piles, the option 'Temporary sheet piles' is chosen. In this option, the production of the steel sheet piles is not taken into account with the underlying thought that they are placed temporary and 100 % recyclable. The pumps for temporary drainage are powered by generators. These generators are running on diesel. Hence, the object chosen to represents the generators is 'Diesel'. It is calculated by the author that approx. 362.200 liters of diesel is used by the generators during the construction. This calculation can be found in Appendix E.1.

Construction

During the construction, the first step is to drive steel piles of the combiwall. A total of 157 piles with a total mass of 1,600 tonnes (with an averaged length around the 29.00 meters and a diameter of 1067 millimeters). For the steel piles of the combiwall, the option 'Steel pile large' is used. Others options like the 'Steel piles large' are not applicable because their have a lifetime of 40 years in DuboCalc. This would mean that 2.5 times as much steel would be used in the case study. This does not represent the reality. The steel sheet piles will be installed next. For the sheet piles, the option 'Steel sheet piles' is chosen. They have a mass of 510 tonnes (PU18 and an averaged length of 14.70 meter).

After this is done, the anchorage should be installed existing of anchor piles of approx. 45-50 meters and a mass of 2.200 kg per anchor and grout with a volume of approx 1.3 m^3 per anchorage (W18-010 BVK aanbrengformulieren-BVK Zuid'). In total, there are 151 anchorages. For the grout of the anchorage, the option 'Grout mortar' is chosen. The anchor piles are not represented in the exercise because non of the four experts had chosen the same object. This is due to a missing appropriate object. As can be seen in the research exercise, this would not have a large influence on the total result.

The concrete construction of the quay wall consists of the concrete mortar C35/C45 CEMIII and rebar. A total of 4,600 m^3 of concrete mortar and 750 tonnes of rebar is used. For the rebar and concrete mortar, the options 'Rebar' and 'Concrete mortar C35/C45 CEMIII' respectively, are chosen. Finally the bed protection is constructed. Firstly, present rubble stone should be removed. This implies 11,720 tonnes of rocks (with a distance of 1 km because it is shipped to a location in the PoR). The object 'Rubble stone' is used with the option 'Released'. Secondly, the protection can be constructed with 1600 tonnes of rubble stone (with a default distance of 15 km) and 35,800 tonnes of reused rocks (with a distance of 1 km, because it comes from a storage location of the PoR). For the bed protection, the DuboCalc object 'Waterbouwkundig gietasfalt' can be used as well. However, this had a lifetime of 25 years which doesn't represent the reality. For that reason, it is not used.

Furthermore, remaining objects (e.g. rigid fendering, life-savings ladder, bolts and other connecting objects) are placed. For the quay wall, the RE-HDPE slabs are repeated every 8.8 meter, hence a total of approx 55 slabs are found on the quay wall. Every slab has a volume of 0.33 m^3 and a mass of approx. 320 kg. This results in a total of 17.6 ton RE-HDPE. The object 'RE-HDPE' is present in DuboCalc. However, this is for RE-HDPE tubes. The emission of the production of RE-HDPE is low, namely 1 ton RE-HDPE emits 1.8 kg CO_2-eq. This results in an emission of 31.7 kg CO_2-eq. This is considerably small and can be neglected further. The life-saving ladder has a mass of 133 kg and is repeated every 29.5 meter. This means a total of 17 ladders and a total mass of approx. 2.3 ton steel. This is a small percentage of the amount of total steel use, hence the ladders are not taken into account further. The bollards are repeated every 17.6 meters and each has a mass of approx. 400 kg. This means 28 bollards and a total steel mass of 11 ton. This is a small percentage of the amount of total steel use and will not be taken into account further as well.

Dredging work

In this phase the excavation of sediments to achieve the desired draught at the quay wall is taken into account. A total of 28.641 m^3 of sludge and 97.511 m^3 of sand needs to be excavated over a distance of 200 meter. For this job, a total of 226.6 tonnes of marine diesel oil (MDO) is used.

In this phase a choice should be made which input is going to be used. The author chooses to take the amount of fossil fuel into account instead of the dredged material in cubic meter.

Maintenance and management

During its life time, the steel sheet piles of the quay wall should be protected against erosion. In HHTT, this is done using MMO-activated titanium electrodes as ICCP. Furthermore, the terminal should be dredged during its life time and remaining maintenance like repairs is included as well.

In DuboCalc, titanium is not present. For this reason, only the amount of electricity in kWh is used to provide protection. This equal to 1.867.490 kWh for 100 year (see Appendix E.2 for the source). Furthermore, the maintenance dredging is not taken into account as it is time specific and not project specific. Thereby it is hard to determine how much this should be during its 100 year lifetime. It is considered out of scope. The remaining maintenance of a quay wall is considerable low and not taken into account further.

5.3. Results of the case study assessment

Filling in the information in DuboCalc, a total amount of 9.11 kt CO_2-eq is emitted for the 479,94 meter south quay wall. For the standard 100 meter quay wall, this results in an emission of 1.90 kt CO_2-eq. The chosen DuboCalc objects include the 30 % fine, as discussed in Chapter 4. This means that the actual emission could be 30 % less. In addition, from the research in Chapter 4, a relative range when using DuboCalc was found of 8.26 %. This results that the lower limit is estimated on 1.17 kt CO_2-eq (-38.26%) and the upper limit is estimated on 2.06 kt CO_2-eq (+8.26%). The author chose to select the 1.9 kt CO_2-eq further into account as the estimated emission for a standard 100 meter short sea quay wall with a life cycle of 100 years. Figure 5.5 is a pie chart visualizing the result in percentages. The detailed results can be found in Appendix E.3. In the case study, the largest contributors are fuels (approx. 36 %) of which temporary drainage and dredging are responsible for the largest emission, steel (approx. 33 %), electricity (approx. 17 %) and concrete (approx. 13 %).

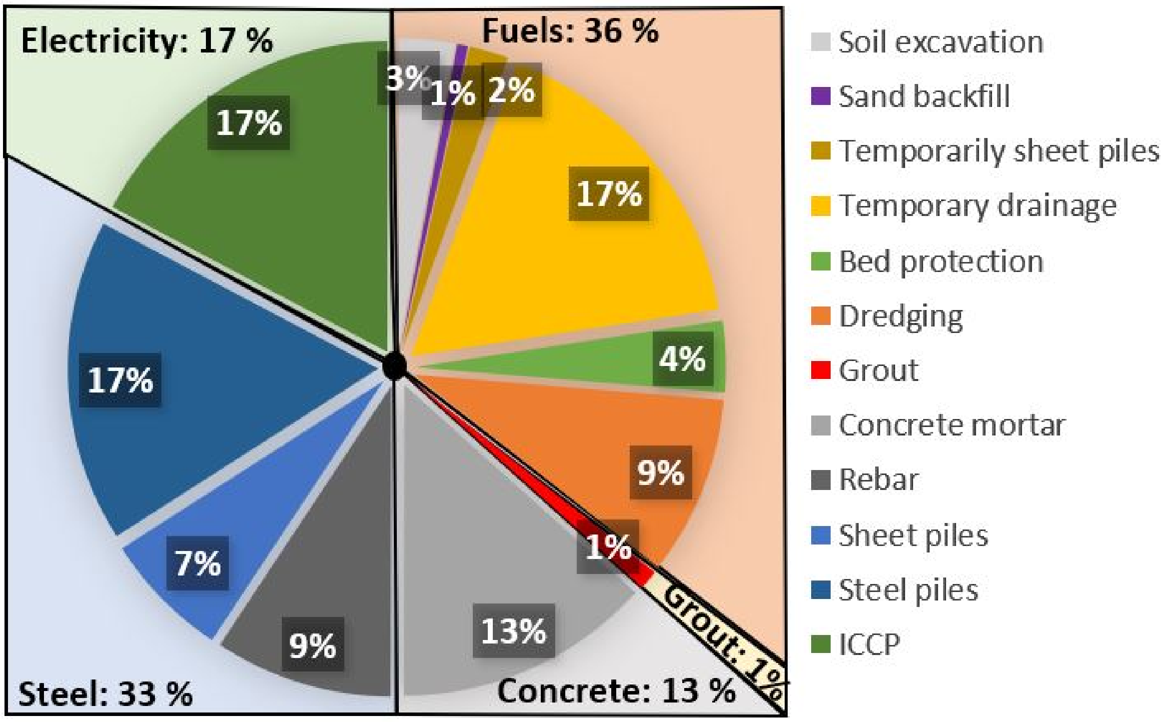


Figure 5.5: Results of the case study expressed in percentages. The objects are grouped per material as well.

6

Determining the intervention measures and the reduction path

6.1. Possible intervention measures

To achieve the set target of being climate neutral in quay wall development, intervention measures are proposed. Possible intervention measures can be arranged in four levels. These levels depend on the technical readiness and the limitations of the measures.

- Level 1: Technical Readiness Level not high enough

  The Technical Readiness Level (TRL) represents the technical progress of the intervention measure. The scale is from one (basic principles are observed and reported) to nine (innovation ready for implementation on a large scale). The TRL is further explained in Appendix F.1. A TRL of seven or lower indicates that the proposed solutions are not technical ready to be applied yet. Further research should be done and it is not advised to use these concepts in quay wall designs yet.

- Level 2: Pilot version

  The proposed solutions in this level are technical ready to be applied (TRL equal or higher than eight), although it is not yet certain if the solutions are applicable on industrial scale. Conducting pilots in commercial designs could help to decide whether or not the solution can be used in quay wall development.

- Level 3: Option menu

  In this level, the proposed solutions are technical ready and can be applied to quay wall development, based on experiences from commercial pilots. However, the applicability of the solution depends on project specific boundaries. Developing a so called 'solution menu' could help engineers to look up possible intervention measures and relate this to their specific project. If the measure fits in the specific project, it can be used.

- Level 4: Standard

  The proposed solutions are technical ready, can be applied to quay wall development and can be generally applied without taking the project specific boundaries into account. These solutions should be become part of the standard quay wall design.

From literature sources and the questionnaires - completed by technical experts - possible intervention measures to reduce the emission of GHG are enlisted. Two categories are found in the measures. The first group are all related to a change in the design and will be further explained in Paragraph 6.2. The second categories consists of improvements of applied materials and will be dealt with in Paragraph 6.3. Detailed calculations of the impact of the various measures can be found in Appendix F.3 to F.10. The possible pathways are presented in Paragraph 6.4. Finally, Paragraph 6.5 will show the required investment costs to execute the intervention measures.

6.2. Change in design

6.2.1. Material changes in design

The materials used in the development of a quay wall have their individual GHG footprint. Table 6.1 presents the different materials used in quay wall development. The related emission of the production of the material, and the related duration of the life cycle are shown as well. What is interesting about this Table is the difference in footprint of concrete and steel. On weight to weight basis, the emission of steel, related to production, is fifteen times larger, compared to concrete. This would mean that in new designs, use of steel should be optimised. Secondly, the use of concrete should be preferred over steel. However, this may mean that the dimensions of the design change as well. Applying the same rebar/concrete density ($\approx 150 \frac{kg}{m^3}$) will cause an increase in the dimensions, resulting in more emission of GHG. If this density could be reduced, the dimensions does not have to be changed. An example how this can be achieved, is to apply Steel Fibre-Reinforced Concrete (SFRC). Less steel is used in this kind of material. However, some problems occur. Firstly, the safety can be an issue. In SFRC, a so called brittle fracture can occur. This means that there is no apparent plastic deformation visible. This leads to unwanted safety issues. Secondly, the solution is still not applicable on technical and commercial scale for quay wall development.

Material	Unit	CO2-eq [kg]	Life cycle [yr.]
MDO	[1 ton]	3.749,92	-
HDPE	[1 ton]	3.194,39	50
Steel	[1 ton]	908,00	100
Grout	[1 ton]	211,43	100
Coating	[1 m2]	181,25	40
Concrete Mortar C35/45 (CEMIII)	[1 ton]	58,04	100
Rubble Stone	[1 ton]	39,87	1.000
Diesel	[m3]	3,30	-
Land Sand	[1 ton]	2,72	1.000
RE-HDPE	[1 ton]	1,85	25
Grey Energy	[1 kWh]	0,65	-
Green Energy	[1 kWh]	0,09	-
Azobe Hard Wood	[1 m3]	-2,22	30

Figure 6.1: Materials in their unit, expressed in kg CO_2-eq

Other materials like tropical hardwood or polythene may be used as a substitute as well. HDPE (polyethylene) is very strong, but its footprint is considerably high. The dimensions should be reduced considerably to decrease the GHG emission. For Recycled High Density Poly Ethylene (RE-HDPE), the emission related to production is low, namely equal to 1.85 kg CO_2-eq per ton RE-HDPE. If enough material is available to apply, it could be a possible good alternative to steel and concrete.

Tropical hardwood can be strong and durable and shows a negative emission of GHG. It can be used as an alternative to RE-HDPE slabs. One hardwood slab has a volume of approx. 7 m^3 (based on the case study). For a 100 meter quay wall, this will result in a negative emission of - 2.8 t of CO_2-eq (55 slabs with a lifetime of 30 years). This is a reduction of 2.9 t of CO_2. This is considerably lower. However, it has three uncertainties. Firstly, the natural conditions of a quay wall is tough: it is exposed permanently (or occasionally at the waterlines) to salt water for a long time period. A chemical process is required to protect the wood, which would increase the GHG emission. Secondly, sustainable management of the forest location, where the wood is sourced from, should be guaranteed. Otherwise it will cause deforestation. Thirdly, it is disputable that tropical hard wood has a negative emission rate. This would mean that more use of the material would mean a better footprint. This causes a situation where the use of the material is better than no use. This is not a realistic assumption.

Change in material could reduce CO_2-eq emission, however designs should be changed and recalculated. More research should be done in these possible solutions. More research in recycled materials like the RE-HDPE is advised, because it may be an applicable solution. That's why it is arranged in Level 1. Hardwood is not considered further.

6.2.2. Quay wall as a CO_2 sink

The possibilities to transform a quay wall into a CO_2 sink is discussed as well. The report RHDHV (2019) suggests that materials like olivine or algae can be part of the construction. Olivine is a mineral that absorbs CO_2. Algae are living organisms that adsorb CO_2 to grow and can be used as food stock. However, this technology is not far enough developed to be considered as a solution and should be researched further more. It is arranged in Level 1.

6.2.3. Extend the quay wall's life time

According to the report of Energy Transition Commission (2018a), significant reductions of GHG emission can be be achieved in the construction phase if the life time of a construction could be extended. The life time of quay walls are not normally limited by the attenuation of materials, but by changing criteria for the use of the quay wall. However, it is hard to predict the future activities at the quay wall. If the loads increase or the draught should be deepened, the design needs to be changed. The life time can be extended through applying a second anchorage. This object reduces the maximum momentum in the sheet-wall and the external stability will remain insides the limits (De Gijt & Douairi, 2013). However, applying a second anchorage to an existing quay wall, is a difficult action. The extra anchor has to be added below the water line from the waterside. A design with a possibility to apply a second anchorage in time could be tested in forms of a pilot. Therefore this measure is arranged in Level 2. However, this measure is outside the scope of a life cycle of 100 years and therefor not taken into account further.

For quay walls in which the loads will most likely not change over the years, an extension of the quay wall's life cycle is not a large investment, when taken into account in the original design of the quay wall. From internal papers of the PoR, the lifetime of a quay wall can be prolonged from 50 to 100 years, by using a factor 1.016 more for steel and a factor 1.032 more for concrete. More concrete is used as the coverage widens. This shows that a small extra investment in the original design, can extend the lifetime of a quay wall significantly. Figure 6.2 shows a sketch of GHG emission for a quay wall of 50 years and a quay wall over a 100 year period.

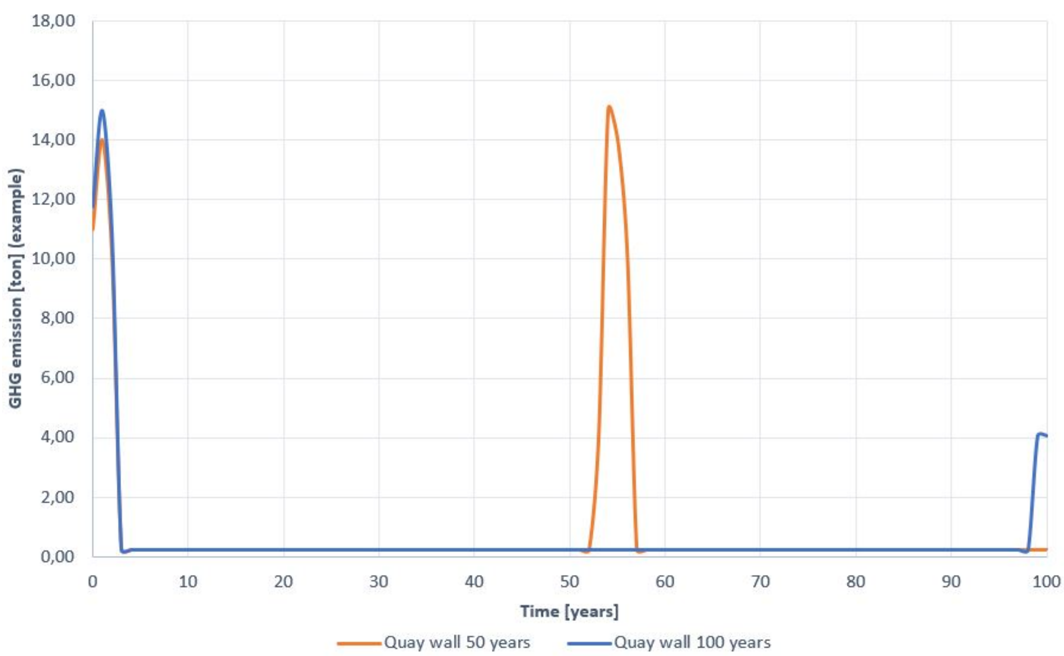


Figure 6.2: An example of the impact on CO_2-eq emission when the life time is extended from 50 years to 100 years. Note that the peak of the orange line around 50 years is larger than the first peak. The production of material and the deconstruction of the quay wall both are in that year, resulting in a higher peak.

6.2.4. Shorten the transport distances

Shorten the transport distance of materials to the construction site, could lead to lower emission rates. It depends on the specific project if the material from closer located production locations is applicable. This is a project specific solution, for which it is not possible to estimate a possible reduction percentage. It is part of Level 3.

6.2.5. Design change with less material use

Shortening of the capping beam

A change in the dimensions of a standard quay wall design has been suggested by an expert of the PoR. A most likely option is the reduction of the length of the capping beam. This would mean a reduction in concrete mortar and rebar. As said before, these are the large contributors to the CO_2-eq emission. Hence a reduction in these materials would have a positive influence. However, shortening the capping beam would mean that the steel sheet plates are exposed to salt water. This would mean that the sheet piles should be treated with a coating. In addition, fenders of wood are applied to avoid damage from the ships to the sheet piles.

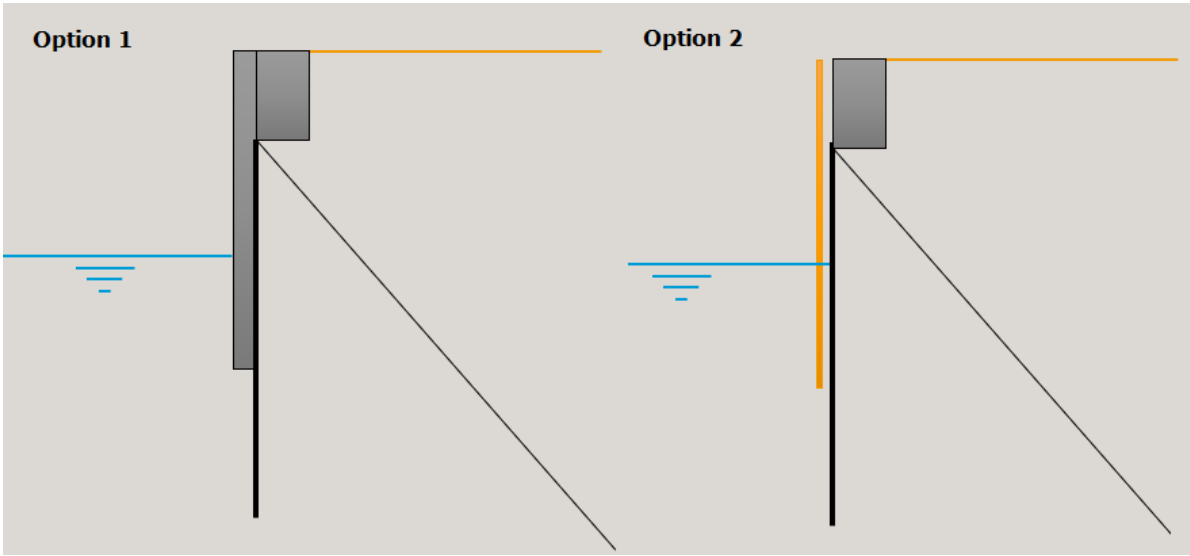


Figure 6.3: The proposed design change of a smaller capping beam. Option 1 is the standard quay wall design for short quay walls. Option 2 is the proposed quay wall design including a smaller capping beam. The orange line in front of the quay wall are the wooden fenders. Source: PoR internal report

The change in design causes a material reduction of 44.35 % of rebar and concrete mortar. Hence a reduction of 44.35 % in emission. However, the necessary coating to protect the exposed surface causes for additional 535 kton of CO_2-eq. The wooden fenders have a negative CO_2-emission. It is collected and stored carbon emission. DuboCalc shows a value of approx. -12 kton . In total, the emission increases with 78 %. This is mainly due to the applied coating that has a large CO_2-eq footprint as well. The calculations can be found in Appendix F.2. From sustainable purpose, it is not recommended to shorten the capping beam. If it had a positive impact on the GHG emission, it would be applicable to all situation and could have been arranged in Level 4. If an alternative coating, with a lower CO2 impact could be identified, this change has the potential to reduce GHG emission.

Downsizing the dimensions: research in piles

The dimensions of the piles used in the quay wall have once been calculated including a safety factor. This safety factor has not been minimized, due to high research costs. At the moment, a large scale research is being executed by the PoR, to decrease the safety factors of these steel piles. If the test ends positive, the piles dimensions can be downsized, leading to a decrease in material and a decrease in emission. This solution can be arranged in Level 2.

6.2.6. A diaphragm wall versus a combiwall

A diaphragm wall can be seen as an appropriate alternative to a combiwall. The difference between these two types of structures is in the substructure. A combiwall consists of steel driving piles and steel sheet piles. A diaphragm wall is made out of concrete and rebar. The construction process of a diaphragm wall is not yet defined in DuboCalc. To compare these structures on their GHG emission levels, only the emissions due to the materials are compared. Internal reports of PoR describe a combiwall and a diaphragm wall that were designed for one quay wall. For a 100 meter combiwall, the driving piles had a mass of 382 ton and the sheet piles had a mass of 167 ton. These are both made out of steel (908 kg $CO2_2$-eq for 1 ton of crude steel). This results in an emission of 500 t CO_2. The diaphragm wall consists of concrete and rebar. In the construction process, bentonite is used. However, there is no emission data on bentonite and will be neglected further. There is 583 ton of rebar used and 3809 m^3 of concrete (density $\approx 150\ \frac{kg}{m^3}$). This results in a GHG emission of 750 ton. This is increase of approx. 50 %. In terms of GHG emission, the combiwall is the better alternative. If it had a positive impact on the GHG emission, it would be applicable to all situation and could have been arranged in Level 4.

Results

Three intervention measures show possibilities for reducing GHG emission. However, further research should be done. The first possible solution is designing a quay wall made out of RE-HDPE. RE-HDPE has a low emission in the production process. Secondly, the research in the piles and the relating reduction of steel is a possible solution as well. Reducing the transport distance is project specific and depended on the contractor. The port authority could steer to lower transport distances in the tendering procedure. Although these solution are worth investigating, they are not taken further into account, as quantification is not possible yet. Table 6.1 shows the proposed solutions and their related levels.

Table 6.1: The design change measures arranged in the TRL levels.

	Level 1	Level 2	Level 3	Level 4
Design lay out	Material changes in design: RE-HDPE	Downsizing the pile dimension	Shorten the transport distances	

6.3. Material improvements

6.3.1. Reduction in the steel production

According to Energy Transition Commission (2018c), a complete decarbonization of the steel industry is achievable by mid-century. However, the report indicates that the public policy and industry investments needs to be redesigned to realise this goal. The target is location-depended as well: locations with low renewable electricity prices will be able to reach low emissions. In Europe, the ULCOS partnership has set a target to reduce at least 50 % CO_2 emissions in 2050. The German steel producer Salzgitter has set a target of 82 % emission reductions by 2050.

Three ways to produce steel are described in the report of Energy Transition Commission (2018c): 1) Blast Furnaces to Basic Oxygen Furnace (BF-BOF), 2) Direct Reduced Iron (DRI) or 3) Electric Arc Furnaces (EAF). BF-BOF produces ore-based new steel which has a 95 % global share. The remaining 5 % of iron based steel is produced in DRI in combination with EAF. In contrast, EAF, which uses scraped steel, consumes electricity and can have a low emission when zero-carbon electricity sources are available. Hence a first solution to reduce CO_2 emission in steel production should be increased recycling of steel. However, Material Economics estimate that already a large part of steel is recycled (around 83 % globally, and 90 % in some developed countries). In addition, scrap based steel could lead to lower quality of steel and circularity is not always possible due to corrosion and copper contamination problems.

The global steel production is expected to increase by 30 % in 2050, hence circularity is not only the answer. Decarbonizing the ore-based steel production should be considered as well. Two main solutions are mentioned in the rapport of Energy Transition Commission (2018c), namely 1) hydrogen used as a reduction agent and 2) Carbon Capture and Storage (CCS). Hydrogen is already part of the DRI ore-based steel production and when applied to construct a hydrogen-based DRI plant, lower emission can be achieved. This is how Salzgitter plans to reduce their emission by 82 % in 2050. Salzgitter will focus on the option hydrogen-as-a-reduction-agent, as CCS is not politically feasible in Germany (Energy Transition Commission, 2018c).

In conclusion, emission can be reduced by increasing circularity, although the percentage is already high, hydrogen use and CCS. The achievable targets vary from 50 % to 100 % reduction. The author choose a reduction of 82 %, following the target of the main producer Salzgitter, as it is one of few that is transparent about their long term targets. When 82 % is reduced in the steel making process, the 100 m standard quay wall will have a total CO_2-emission of 1.46 kt CO_2-eq . This is a reduction of 24 % of the current situation. The calculations can be found in Appendix F.3. This will be taken further into account in the possible reduction path (Paragraph 6.4). The solution is arranged in Level 1, as it is still not technical feasible.

6.3.2. Reduction in dredging: fuel change

The fuels used for dredging can be changed as well. Table 6.4 shows the alternative fuels, their CO_2-eq footprint per tonne and their energy volume [MJ/kg]. These values are averages. If the actual emission reduction potential is required, more research should be done in specific engines with their related efficiencies. However, for this report it is assumed to be representative for dredging operations. Liquefied Natural Gas (LNG) is a common alternative fuel. According to the Table 6.4, it does not reduce the amount of CO_2 in its full life cycle. However, the energy volume [MJ/kg] is higher for LNG (49 MJ/kg) than for MDO (42 MJ/kg) (Jochemsen-Verstraeten et al., 2016). This means that less volume of LNG is required than MDO. LNG generated ships need to change their engines causing extra costs. Bio-fuels like Hydrotreated Vegetable Oil (HVO) (44 MJ/kg) have a smaller footprint and does not require to change the engines. It is possible to reduce emissions with approx. 75 %. But it is a transition fuel (it is not a final solution) and is not able to be produced on a global scale. In addition, it is more expensive. Hydrogen in this topic is produced 50 % with renewable electricity (approx. 120 MJ/kg) and does reduce the footprint with approx. 66 %. In the future, if hydrogen is produced with 100 % renewable energy (green hydrogen) is available, this could be a applicable solution. However at the moment, it is not technical ready yet to be applied.

Material	kg CO2-eq/ ton	MJ/kg
Marine Diesel Oil (MDO) [1 ton]	3749,92	42
Liquefied Natural Gas (LNG) [1 ton]	3987,11	49
Hydrotreated Vegetable Oil (HVO) [1 ton]	979,46	44
Hydrogen in fuel cells (50% green) [1 ton]	3594,29	120

Figure 6.4: Fuels in their unit, expressed in kg CO_2-eq

To have an indication of the emission reduction it is necessary to compare the fuels, based on the energy content per weigh. This can be done with the energy volume values and a simplified calculation. If LNG is chosen (40.48 ton of LNG), an total emission of 1.88 kt is found. This is a decrease of 2 %. For 45.08 ton of HVO, a total emission of 1.77 kt is found (reduction of 8 %). The fuel hydrogen in fuel cells (16.53 ton) results in a total emission of 1.78 kt (a decrease of 7 %). If green hydrogen is assumed, a total emission of 1.72 kt is found (a reduction of 10.4 % is found). Knowing that green hydrogen is not technical feasible and not available on commercial scale yet (Level 1), the fuel HVO would be an applicable solution to reduce the GHG emission for now. It is assumed that green hydrogen is a possible solution in 2050. The calculations can be found in Appendix F.4. This will be taken further into account in the possible reduction path (Paragraph 6.4). The HVO solution is arranged in Level 4, as it is possible on commercial scale and not project specific.

6.3.3. Reduction in the heavy duty road transport

During the life cycle of the quay wall, CO_2-eq is emitted due to heavy duty transport. These emissions are caused by the use of Internal Combustion Engines (ICE). According to Energy Transition Commission (2018b), both the use of alternative low-carbon fuels within internal combustion engines, a shift to electric drivetrains with energy storage in battery (Battery Electric Vehicles or BEVs) or hydrogen (Fuel Cell Electric Vehicles or FCEVs) form, are the most likely options for emission reduction. Biofuels and synthetic fuels are more expensive at the moment (and likely in the future) compared to diesel and gasoline. Therefore, they are not going to be a major solution for decarbonizing transport. However they are more likely to be a transitional fuel for the very-long-haul applications, if low hydrogen prices cannot be achieved.

The advantages of ICE are their energy storage efficiency compared to BEVs and volume advantages compared to hydrogen. However, the energy efficiency of electric drivetrains is around 95 % and for FCEV's it is around 60%. ICE trucks energy efficiency is around 40 %.

Nikola produces hydrogen-powered electric semitrailer truck, build for the European market. Hydrogen stations are planned to be build around 2022, aiming to cover most of the European market by 2030. According to the report of Energy Transition Commission (2018b), the decarbonization will consist of a switch to electric drivetrains, with BEVs playing a major role. Further away in time, hydrogen FCEVs and catenary overhead wiring of major roads are likely to play a significant role in the long-haul sector.

Expected is that long-haul BEV trucks will become cost-competitive in Europe sometime between 2023 and 2031. Regional haul (200 km) trucks and urban haul (100 km) trucks and buses will however enjoy a cost advantage much earlier, with the economics supporting large-scale deployment by the mid-2020s. However the upfront cost of FCEVs might stay higher for the foreseeable future.

To conclude, it is expected that electricity BEV trucks, using renewable electricity, will be fully exploited in 2025 for regional haul trucks and urban trucks. The transport distances from storage location to construction location are shorter than 200 km in DuboCalc. The reduction will be set to 100 % in 2025. However, a reduction of 100% is too optimistic. The production of the truck and the generation of the renewable electricity will cause emission. This is assumed to be small enough to be neglected (and machinery efficiency is not known, so a complete comparison between fuel and electricity can not be made). When 100 % is reduced in the heavy duty road transport, the 100 m standard quay wall will have a total CO_2-emission of 1.86 kt CO_2-eq. This is a reduction of 3 % of the current situation. The calculations can be found in Appendix F.5. This will be taken further into account in the possible reduction path (Paragraph 6.4). The solution is arranged in Level 2, as it is technical feasible but not on commercial scale yet.

6.3.4. Reduction in the concrete production

Long term reduction in the concrete production process is one of the most difficult challenges, according to (Energy Transition Commission, 2018a). To decarbonize the cement production, the GHG that occurs in the chemical processes in which limestone is converted into calcium oxide, and the energy needed to produce heat for the kilns should be eliminated.

The fossils fuels needed for the heat could be replaced by electrification, the use of biomass or the use of hydrogen. Electricity from renewable sources is possible in theory although industrial scale electric cement kilns do not yet exist. Further research should be done. Biomass as a fuel would require a slight change to existing kilns. However, whether the supply of biomass can hold up with the demand is uncertain, as it is a solution that is attractive to multiple industries. It can be seen as a transition fuel, rather than a long term solution. Green hydrogen can be a solution as well, although significant furnace redesigns should be invented.

For the chemical process, new cement chemistries are researched, but due to scarcity of the resource (minerals) supply, properties are different and a full conversion to a carbon free process is not expected. Geo-polymer-based-cements could contribute to a reduction of 70 % and the minerals are more likely to be available. However, these products are highly chemical and at the moment are only used in prefab structures. Examples of geo-polymer-based-cements are Reduton and SQAPE. In the short term, the recycling of concrete could have a relative large influence. Freement concrete is based on recycled concrete, according to the producer, this could reduce emission with 40 % to 45 %. According to (Energy Transition Commission, 2018a), a GHG free process will require CCS, resulting in significant higher costs. Figure 6.5 gives an overview of the possible solutions.

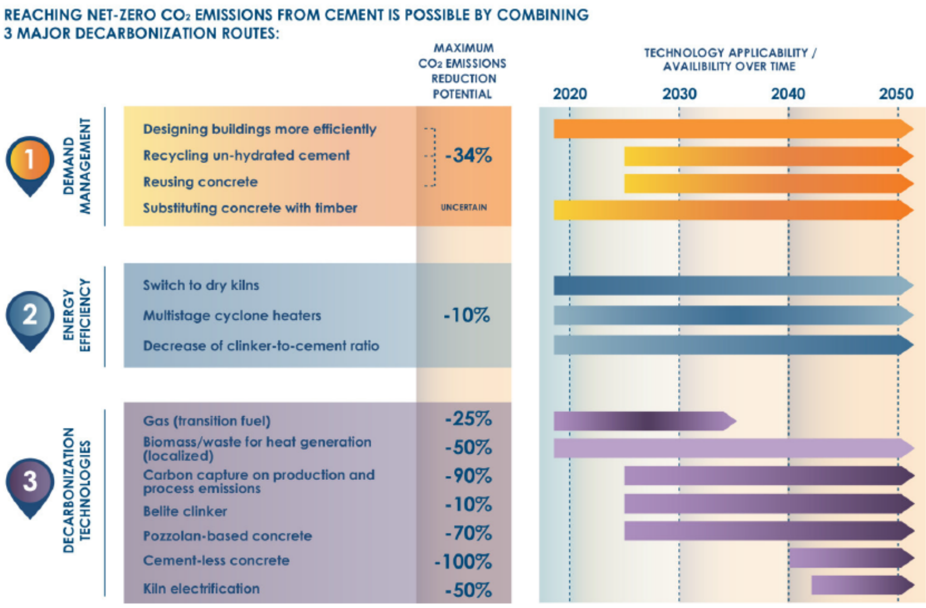


Figure 6.5: Reaching net zero CO_2 emissions in the concrete production. Source: (Energy Transition Commission, 2018a)

A pathway to full decarbonize the cement production is not described yet as the Cement Sustainability Initiative (CSI) stated. A most likely scenario developed by Material Economics, in which concrete is recycled, suggests that European construction emissions for concrete in 2050 could be reduced up to 45 %. This would mean for the 100 meter quay wall a total emission of 1.84 kt CO_2-eq (a reduction of 4 %). In the PoR, the plans to roll out a full commercial CCS facility (Porthos) in 2030 are in process. If a CCS infrastructure is developed and the concrete production could make use of it, the reduction percentage could even increase to 90 %. This would mean a reduction of 9 %, resulting in a total emission of 1.75 kt. The calculations can be found in Appendix F.6. This will be taken further into account in the possible reduction path (Paragraph 6.4). The solution is arranged in Level 1, as it is still not technical feasible.

6.3.5. Reduction in the construction machinery

Electrification

The emission of construction machinery is due to the use of fossil fuels in ICE. Transforming the machinery to all-electric equipment can lead to a potential 1.9 Mton of CO_2 reduction in the Netherlands (Jones, 2019). Additional benefits include noise reduction, zero-emission, more efficient and a lower cost of ownership (Jones, 2019), (SKOA, 2018).

Popular brands for construction equipment starting with electrifying their urban fleet. Volve CE will stop developing diesel generated machinery and start selling all-electric excavators and wheel loaders at the moment. Companies like Bobcat, JBc, Caterpillar and Wacker Neuson are selling (compact) excavators as well (Jones, 2019). In addition, Wacker Neuson develops all-electric forklifts and wheel dumpers (SKOA, 2018). The company BYD has developed an all-electric dumper with a capacity of 10.6 cubic meter (Energy Markets & Technology, 2019).

It should be said that the logistics will need to be changed when working with battery powered equipment, but this should not be a challenge. Working with cable powered equipment can be more challenging logistically, although the range is limitless. A combination of the two is also a possibility (Energy Markets & Technology, 2019).

The battery technology is developing fast with reducing costs. According to Energy Markets & Technology (2019), this rapid developing technology should make it possible to fully electrify the construction machinery in 2030. Assumed is that renewable electricity has zero emission in this example (machinery efficiency is not known, so the comparison of fuel to electricity can not be made) and the GHG emission can be reduced up to 90%. This leads to a reduction of 11 %, resulting in a total of 1.71 kt. The calculations can be found in Appendix F.7. This will be taken further into account in the possible reduction path (Paragraph 6.4). The solution is arranged in Level 2, as it is not available on commercial scale yet.

Other fuels

Other fuels like bio-fuels (HVO), LNG and hydrogen can be applied as well. But as discussed in the other reduction options, bio-fuel is a transition fuel and is not able to produce on a global scale. In addition, it is more expensive. The reduction potential of LNG is relatively low and the technology behind hydrogen is not developed enough yet.

6.3.6. Reduction in electricity generation

The ICCP currently runs on fossil electricity. If renewable electricity is used, the emission can be reduced with 86.69 %. This will result in a reduction of 15 % of the total sum. The total emission of a 100 m quay wall is equal to 1.64 kt CO_2-eq. Renewable electricity is still not emission free due to the LCA method. The construction of renewable sources contributes to the emission of renewable electricity. This will be taken further into account in the possible reduction path (Paragraph 6.4). The solution is arranged in Level 4, as it is possible on commercial scale and not project specific.

6.3.7. Reduction in the temporary drainage of the construction pit

The electricity needed for the temporary drainage systems is responsible for a large part of the emission (16.4 %). These systems are electrical driven but the electricity is provided by the diesel generators. Providing an electrical grid to the drainage systems, will make the diesel generators superfluous. It is challenge however to have electricity available on time at a quay wall construction site from the start. Neglecting the emission of the equipment, the diesel in liters should be translated into energy (kWh). From internal report of the PoR, it is known that the generators 150 kVA consume 20,4 liter per hour. This means that when it is translated to one generator, it needs to work for 17,753 hours (362,177.0/20.4). In reality, multiple generators are present. According to GrandVoltage (2019), the generators have a power of 120 kW. This result in a required energy of approx 2.130.300 kWh. If this is going to be provided by fossil electricity, it will result in an increase of 3 % and a total of 1.97 kt for the 100 m quay wall. If renewable energy is possible, a reduction of 14 % and a total emission for the quay wall of 1.65 kt CO_2-eq. This is further elaborated in the reduction path. The solution is arranged in Level 3, as it is possible on commercial scale but it is project specific.

The difficulty is that an electrical connection needs to be present in the construction phase. For brownland construction sites, a connection could be available as the previous activities on the quay wall require electricity. However, greenfield construction sites doesn't have such a connection, although this will most likely be required over the years. This means that the construction planning and facilitation should be changed.

Results

The material improvements show possible intervention measures that can be quantified. This will be used in the next Paragraph. Table 6.2 shows the proposed solutions and their related levels.

Table 6.2: The possible measures arranged in their possible levels

	Level 1	Level 2	Level 3	Level 4
Material improvements	Production of steel with a lower CO_2 emission	Electric machinery	Temporary drainage on renewable energy	ICCP on renewable electricity
	Dredging operating on hydrogen	Electric operating heavy duty transport		Dredging operating on HVO
	Production of concrete with a lower CO_2 emission			

The following material improvements are taken into account:

- As from 2020, make renewable electricity available for the temporary drainage systems and for the ICCP.
- As from 2020, change MDO to HVO and in the long term (2050) to hydrogen for dredging.
- Research into prefab concrete quay walls with geo-polymer-based-cements.
- BEVs are used as from 2025.
- Applying concrete with CCS and electrified machinery in 2030.
- Applying steel with hydrogen-as-reduction-agent in 2050.

6.4. Possible reduction path

6.4.1. The timeline

The various intervention measures are further elaborated in this sub Paragraph. Figure 6.6 represents the development timeline of the discussed intervention measures. The related reduction in GHG emission is shown as well. It can be seen that the emission decreases step wise from 1.90 kt in 2020 to 0.28 kt in 2050. The calculations can be found in Appendix F.3 to F.10. The different years will be discussed in the following sub Paragraphs.

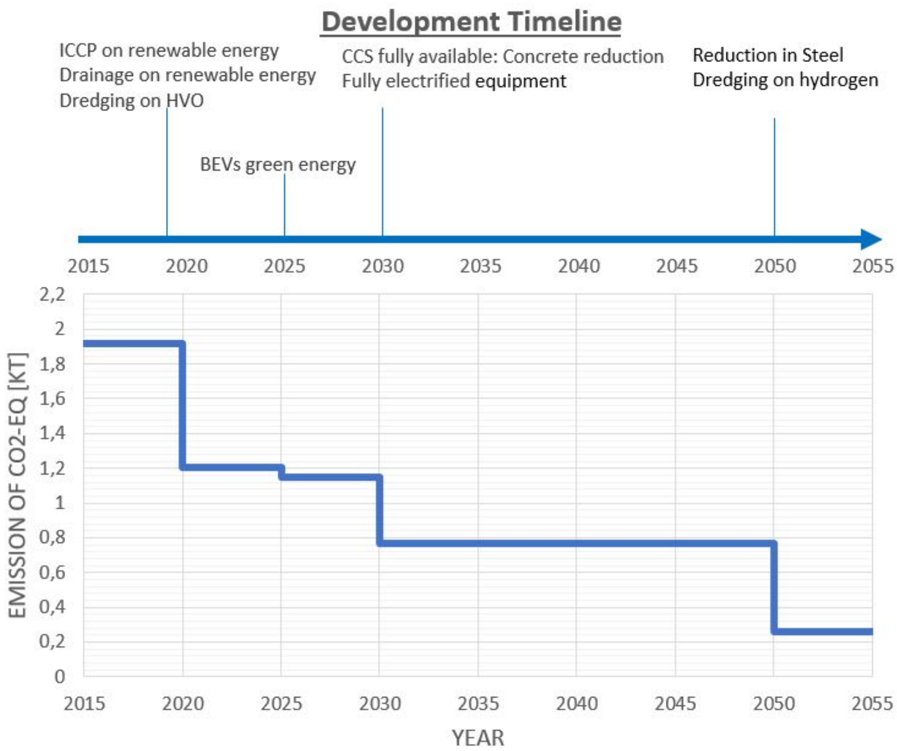


Figure 6.6: Development timeline

6.4.2. The potential at the moment

As from 2020, it is possible to reduce 37 % on the GHG emission of the 100m standard short sea quay wall. This is done by making renewable electricity available for the temporary drainage systems and for the ICCP. A different fuel, namely HVO, could be used to reduce the emission due to dredging. Figure 6.7 represents the reduction of emission and the remaining GHG emission. If these measures are conducted, the total GHG emission of a standard short sea quay wall can be estimated at 1.21 kt CO_2-eq.

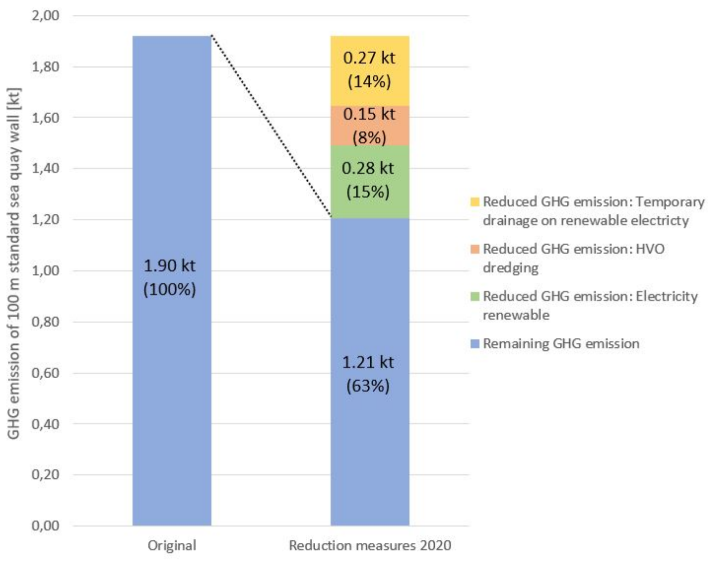


Figure 6.7: Possible reduction scenario at the moment

6.4.3. The potential in 2025

In 2025, BEVs trucks are likely to become standard in the market. This will cause a further reduction to 40 % of the current emission. This is a change of 3% to the 2020 scenario. This is represented in Figure 6.8. However this is only a small contributor. The total GHG emission of a standard short sea quay wall will be equal to 1.15 kt CO_2-eq.

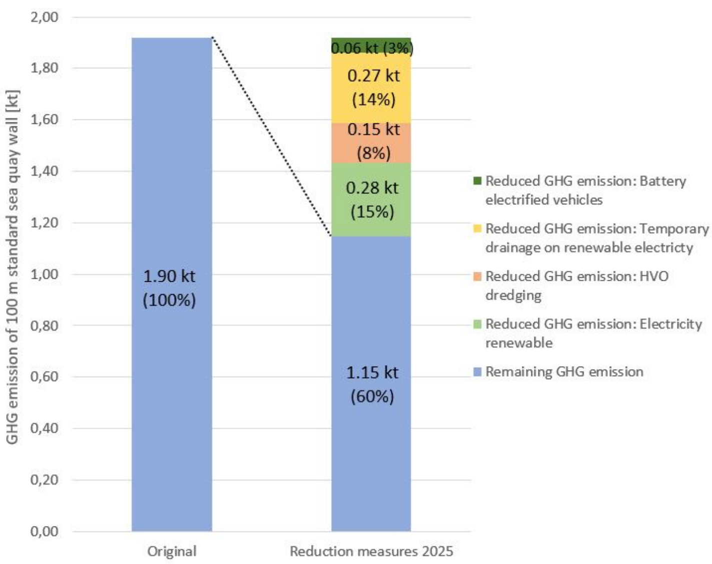


Figure 6.8: Possible reduction scenario in 2025

6.4.4. The potential in 2030

In 2030, it can be expected that the construction equipment fleet will be fully electrified and economically feasible. In addition the CCS project aims to be fully exploitable in 2030 which could lead to a reduction of GHG emission in concrete production. These two intervention measures will cause a further reduction to 60 % of the current emission. The total GHG emission of a standard short sea quay wall will be equal to 0.77 kt CO_2-eq. This is represented in Figure 6.9.

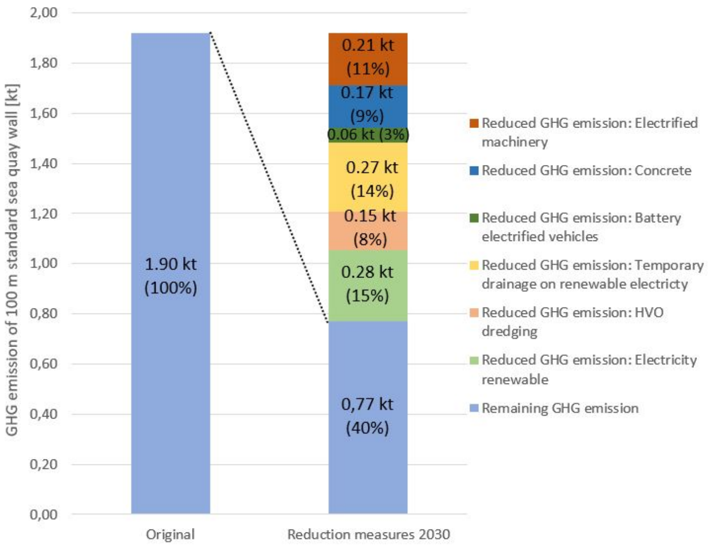


Figure 6.9: Possible reduction scenario in 2030

6.4.5. The potential in 2050

In the target year 2050, it can be expected that the emission of BF-BOF steel production is with 82 % reduced. In addition, hydrogen for dredging will be available on commercial scale. This will cause a further reduction to 86 % of the current emission. The total GHG emission of a standard short sea quay wall will be equal to 0.26 kt CO_2-eq. This is represented in Figure 7.3.

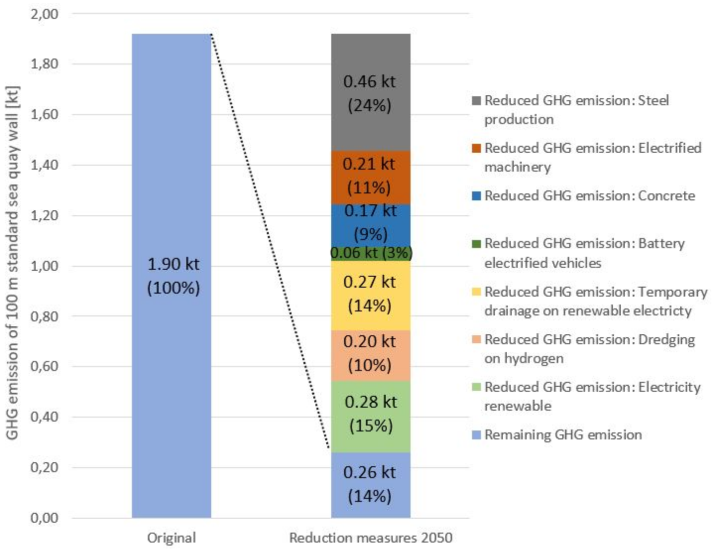


Figure 6.10: Possible reduction scenario in 2050

Summing up all the reduction measures gives an indication of possible maximal reduction of a 100 m quay wall in 2050. This is the date of the target. The result is that the emission of 100 meter quay wall can be reduced with 1.64 kt CO_2-eq (86 %) in 2050. However, an emission of 14 % remain. The target of being climate neutral in 2050 is not possible based on these estimations.

6.5. Investment in GHG reduction

6.5.1. Introduction

The possible intervention measures and the related year of adaption are described. However this doesn't give an answer on the research question yet. It is interesting to see which price should be invested to make these solutions possible on commercial scale. This is expressed in invested euro per ton CO_2-eq (€/ton CO_2-eq) and will be further elaborated for the applied intervention measures.

6.5.2. The costs in the dredging fuel

Hydrotreated Vegetable Oil

One ton of MDO emits 3.75 t CO_2-eq. The energy volume is equal to 42,000 MJ per ton. HVO has a energy volume of 49,000 MJ per ton and emits 0.979 t CO_2-eq. If the emission of MDO and HVO are compared, it means that one ton of MDO is equal to 0.95 t of HVO. This is equal to 0.935 t CO_2-eq. This means a reduction of 2.815 t CO_2-eq. The price of MDO is equal to 350 € per ton and the price of HVO is equal to 830 € per ton (Kiefel & Lüthje, 2018). This results in a price difference of 480 €. Hence an extra carbon investment of 170 € per ton CO_2-eq reduced is required to make MDO competitive.

Hydrogen as fuel

Green hydrogen doesn't exist on commercial scale, hence a production price doesn't exist. However, renewable energy is much dependent on low renewable energy prices. According to Gasterra (2019), green hydrogen production on a commercial scale is only possible when CO_2-eq prices rise to around 60 euros and renewable electricity prices are around 20 euros per MWh. This is not taken into account further.

6.5.3. The costs in steel production

As discussed before, it is assumed that the 82 % of GHG emission in steel production is achieved in 2050. This emission reduction is based on hydrogen as the reduction agent in ore-based steel production. The possibility of CCS is also discussed. According to Witteveen et al. (2018), the possibility to achieve the target depends mainly on renewable electricity prices. Figure 6.11 visualises the needed carbon price per ton emission ($/tonne CO_2) in relation with the renewable electricity prices. The different lines visualise the hydrogen as reduction agent option, the CCS option or biomass (biomass was neglected in this report). If the current wholesale price for renewable electricity in the Netherlands is taken into account (equal to 75 € per MWh (CBS, 2019), with current currency exchange rate 1 € = approx. 1.10 $, hence 82.5 € per MWh), the required carbon price can be determined. To make CCS possible for the steel production, the carbon price should be equal to 125 $ per ton (113 € per tonne) (point 1 in Figure 6.11). For hydrogen-as-reduction-agent option, a carbon price of 210 $ per tonne (191 € per tonne) is required (point 2 in Figure 6.11). For this report, the reduction in the steel production is based on the German steel producer Salzgitter. According to Energy Transition Commission (2018c), Salzgitter will focus on the option hydrogen-as-a-production-agent, as CCS is not politically feasible in Germany. That is why the CCS option in steel production is not taken into account further in this report. Note that hydrogen production based on renewable energy is not available on large scale yet.

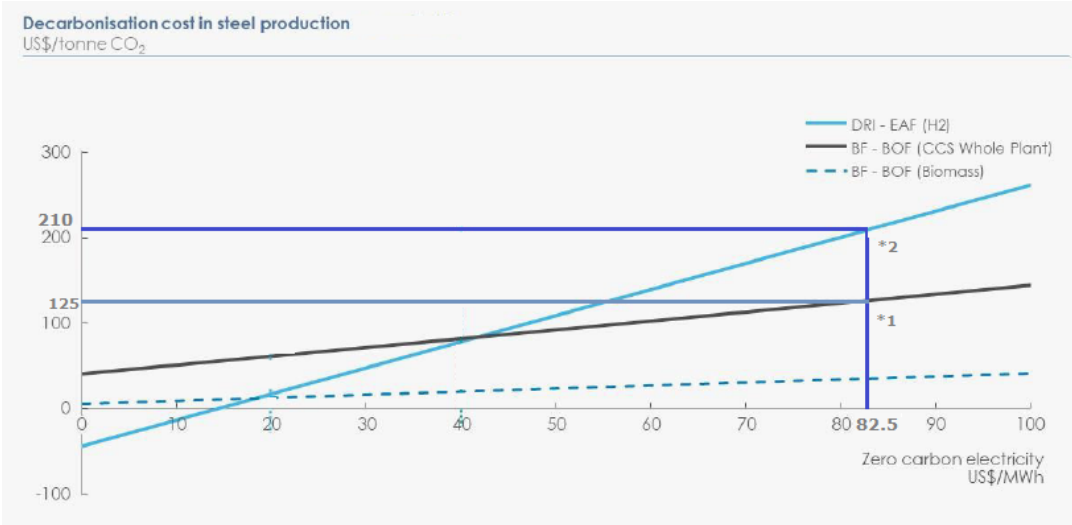


Figure 6.11: The decarbonisation costs in the steel production. At the current market price of renewable electricity in MWh in the Nederlands, the correlated carbon price for CCS is 125 $ (point 1) and for hydrogen-as-a-reduction-agent is 210 $ (point 2). Source: (Witteveen et al., 2018)

6.5.4. The costs of the heavy duty transport

According to (Energy Transition Commission, 2018b), zero-carbon trucks are expected to be cost-competitive industrial countries in the 2020-2030 period. The costs of shifting to electric vehicles will be around null. However, the infrastructure should be changed as well, which will have a cost. The ETC calculated that this transition will cost around the 10 $ and 20 $ per tonne CO_2. In this report, the required carbon price is assumed to be 20 € per tonne CO_2, in order to be economical beneficial.

6.5.5. The costs in the concrete production

In this report, it is concluded that a concrete production plant with a CCS is the most promising solution to reduce GHG emission. This could lead to a reduction of 90 % in the concrete production process. According to Witteveen et al. (2018), the solutions and relative carbon price are depended on renewable electricity prices. With the current wholesale renewable electricity prices in the Netherlands (82 $ per MWh), the carbon price per option can be determined. Figure 6.12 shows the decarbonization costs in cement production. Option 1, CCS for the full production (heating and chemical process), would be profitable with a carbon price of 180 $ per tonne (164 € per tonne). Option 2, electrification with CCS, a carbon price of 210 $ per tonne (191 € per tonne) can be found. Option 3, hydrogen with CCS, would be profitable if a carbon price of 300 $ per tonne (227 € per tonne) is asked. For this report, option 1 is assumed to be applied and will be elaborated further.

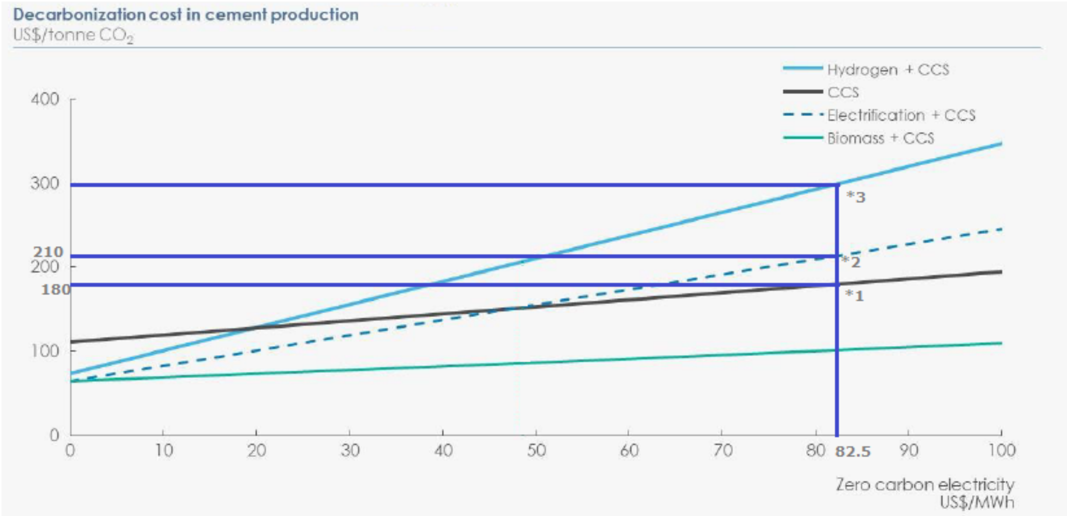


Figure 6.12: The decarbonisation costs in the concrete production. At the current market price of renewable electricity in MWh in the Netherlands, the correlated carbon price for CCS is 180 $ per ton (point 1), for electrification with CCS is 210 $ per ton (point 2) and for hydrogen + CCS is 300 $ per ton (point 3). Source: (Witteveen et al., 2018)

6.5.6. The costs in the construction machinery

Electrification of the construction machinery is another promising solution. According to Energy Markets & Technology (2019), the carbon price should be depended of the price ratio of taxed diesel and taxed renewable electricity and the investment costs of new electrified machinery. Although, the report doesn't answer the carbon price, it explains a business game for an excavator with a lifespan of 15,000 hours. This could give an indication of the required carbon price. The price ratio of taxed diesel and taxed renewable electricity is approx. equal to 1.5 in the Netherlands (price renewable electricity = 0.075 € per kWh, price taxed diesel = 1.23 € per liter with energy content = 10.1 kWh per litre, hence diesel = 0.12 € per kWh). Two options for the investment costs are considered: costs for electric excavator are 1) 200 % more expensive or 2) 50 % more expensive than a diesel generated excavator. Figure 6.13 represents the business game. It shows that if option 1 is assumed, an additional of 100,000 € is required to make it economical beneficial. If option 2 is assumed, the total costs are reduced.

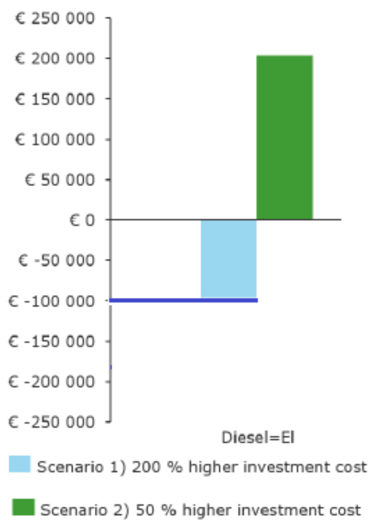


Figure 6.13: The business game of a diesel generated excavator or a electric excavator. Source: (Energy Markets & Technology, 2019)

A diesel generated excavator with 15,000 working hours emits approx. 790 ton CO_2-eq. An electric excavator emits with the same working hours 79 ton CO_2-eq (a reduction of 90 %). This is a reduction of 710 ton CO_2-eq. This means that 710 ton is reduced with a cost of 100,000 €. Hence a carbon price of 140 € per tonne CO_2-eq. The prices of electric excavators is not known, although it is expected to decrease rapidly as the battery prices decreases as well (Energy Markets & Technology, 2019). However, in this report option 1 is assumed and will be elaborated further.

6.5.7. The costs of the transition from fossil electricity to renewable electricity

The transition from fossil electricity to renewable electricity is the most promising solution in GHG emission reduction. This report shows a reduction of 0.56 kt CO_2-eq per 100 meter standard quay wall. The generation of renewable energy is more expensive in the Netherlands. However, it is subsidized by the government causing lower prices. According to Consumentenbond (2019), the costs at the delivering companies for renewable and fossil electricity are almost equal in the Netherlands. Assuming that the PoR can receive renewable electricity at the same cost as fossil electricity and the temporary drainage systems can be connected without any additional costs, the carbon investment is equal to zero.

6.5.8. The costs of using renewable electricity instead of diesel for temporary drainage

The transition from diesel to renewable electricity could lead to a reduction of 0.25 kt CO_2-eq per 100 meter standard quay wall. The price of renewable electricity is 0.075 € per kW and the price for untaxed diesel is 1.23 € per liter. It was calculated that 362,000 liter was used which results in 445,000 €. The calculated required energy was 2,130,300 kWh which results in 160,000 €. The costs are lower for using renewable energy. Hence the investment cost are zero. This will be further elaborated. However, the costs of different equipment is not taken into account which could increase the prices for renewable energy.

6.5.9. The investment cost in conclusion

To conclude the investment costs, the following Figure summarises the investment in ton emitted CO_2-eq, expressed in €/ ton CO_2-eq, to the total possible reduction of the 100 m quay wall (see Figure 6.14).

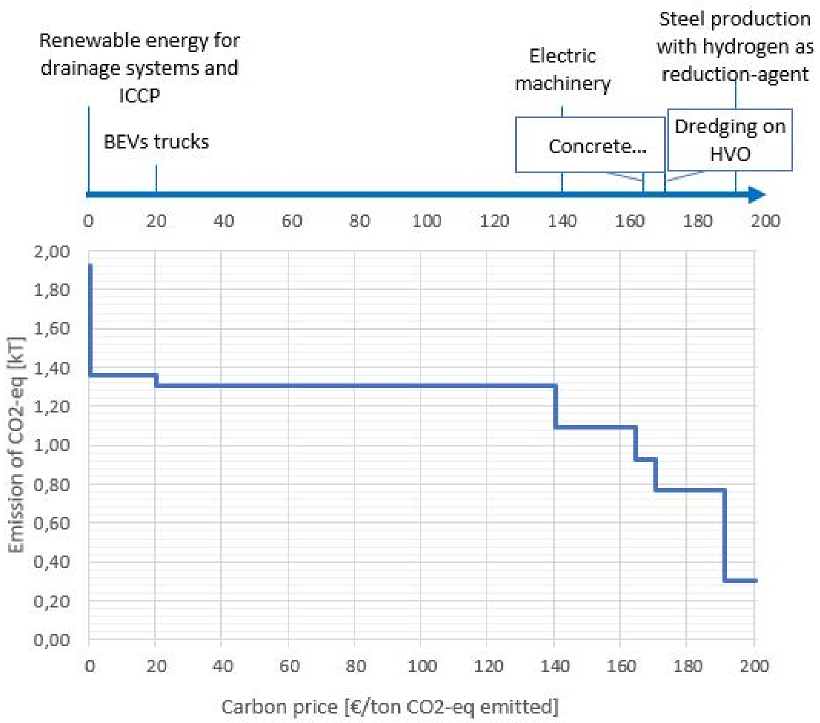


Figure 6.14: The carbon prices of the various options and their potential reduction. The carbon price is expressed in €/ ton emitted CO_2-eq.

6.6. Results of possible intervention measures

This Chapter showed that in the design changes more research should be done, although three solutions are favorable: quay walls made out of RE-HDPE, the dimensions of steel piles and prefab concrete quay walls with geo-polymer-based-cements. For the material improvements, the PoR should focus on the largest contributors of GHG emission. The following actions are advised:

- As from 2020, renewable energy could be used for the Impressed Current Cathodic Protection (ICCP) which could lead to a reduction of 15 %. The transition from fossil electricity to renewable electricity is without extra investment costs.
- Secondly, using renewable energy instead of diesel for the temporary drainage systems will reduce the emission with 14 %. Including previous actions a total reduction of 29 % is achieved. The costs of the amount of renewable electricity is lower than the required amount of diesel.
- Thirdly, if the PoR will invest approx. 170 euro for every saved CO_2-eq, Hydrotreated Vegetable Oil (HVO) can be used as an alternative fuel for dredging to reduce emission with 8 %. Including previous actions a total reduction of 37 % is achieved.
- Further research could be done in alternative designs. This could lead to a reduction in concrete and steel use, as they are the larger contributors. Alternative designs includes quay walls made out of Recycled High Density PolyEthylene (RE-HDPE), smaller dimensions of steel piles and prefab concrete quay walls with geo-polymer-based-cements.
- The evaluation procedure in which the quay wall is monitored every five years, could be implemented. This will help to evaluate the applied intervention measures and to oversee if the targets are going to be achieved. It will be part of the strategical planning of the PoR.
- Furthermore, the PoR could encourage the contractors to use electrified transport (on commercial scale around 2025) and machinery (on commercial scale around 2030) resulting in a emission reduction of 3 % and 11 % respectively. Including previous actions a total reduction of 51 % is achieved.
- Finally, anticipate long term technical innovation in concrete with Carbon Capture and Storage (CCS) (on commercial scale around 2030), hydrogen as dredging fuel (on commercial scale around 2050) and steel with hydrogen as reduction-agent (on commercial scale around 2050). This could reduce emission with 9%, 10 % and 24 % respectively. Including previous actions, except use of HVO, a total reduction of 86 % is achieved.

7

Discussion, conclusions and recommendations

7.1. Discussion

In this Paragraph, the assumptions made and the corresponding limitations of the findings are discussed. This will be described per research question and in general.

In relation to research question 1

The first limitation that occurs is the representation of applied FoSPI to quay wall development in the PoR. The FoR method intends to include discussion with various stakeholders and multiple discussion rounds to evaluate the feedback. However, the author has chosen to discuss all aspects shortly based on the literature sources. The prioritized topic by the PoR, the emission of GHG, has been fully elaborated. This limitations may cause a simplification in the assessment of sustainability topics. This can be solved by conducting more interviews with stakeholders in the non-prioritized topics.

In relation to research question 2

A second limitation is the representation of the tool DuboCalc and its results. The conducted research has a relatively small pool (n=4). A small pool leads to a lower reliability in the concluded deviations. If the research is repeated, it is most likely the results will not be fully equal. The reason why the pool was small, is because the research was dependent on third parties who work with DuboCalc. Unfortunately, this amount is low. However, the author is convinced that the results provide valuable insight into the shortcomings of the use of DuboCalc for GHG emission assessments.

A third limitation, is whether the database that is implemented in DuboCalc is up-to-date. This influences the result of the current emission in the life cycle of the 100m standard short sea quay wall. In Chapter 4, it was concluded that the NMD is a reliable database commonly used in the Netherlands. In DuboCalc however, the author found it difficult to identify the relating data sources and years. The reference to the literature source was not unambiguously noted. When considering GHG emission data, it is important that the information is up-to-date as technology improves. In Table 7.1, the largest contributors are considered. In the Table, the DuboCalc emission value is compared to other literature resources. It can be seen that for most materials, the DuboCalc value is slightly higher compared to the other identified values. However, for steel, the found values fluctuate from approx. 50 % to 220 %. The source in which the 0.9 t/t was found originates from 2003 which is almost 17 years ago. Steel is responsible for approx. 33 % in the case study. If the emission rate changes, it will have a large impact on the results. The other identified values are more up-to-date. For now, the author uses this data because it is an average of the other identified values, although it is expected that this value may change if more research is done. In addition, the used objects of DuboCalc are categorized in category 3 and have an 30 % fine. This means that 30 % is added to the total emission. In this research, this is included in the result. However, in reality, this result could be 30 % lower. However, the author did not chose to do so, as this will be against the protocol of DuboCalc. Nonetheless, if this data is used in the tender procedure, the result will most likely be reduced with 30 %.

Table 7.1: Comparing the input data of DuboCalc materials to other literature sources

Material	CO_2-eq	Source	Note	Min - Max	Sources
Steel	0.9 (t/t)	(Bouwen met Staal, 2003)	Based on averaged construction steel produced in west-Europe and adapted to the dutch market.	0.5 - 2.1 (t/t)	(Meijer & den Hollander, 2013) - (Energy Transition Commission, 2018c)
Diesel	3.3E-3 (t/l)	NMD	From database DuboCalc	3.2E-3 (t/l)	(Otten et al., 2015)
Fossil electricity	6.7E-4 (t/kWh)	NMD	From database DuboCalc	6.5E-4 (t/kWh)	(Zitzen et al., 2017)
Renewable energy	9E-5 (t/kWh)	NMD	From database DuboCalc	0 - 8E-5 (t/kWh)	(Zitzen et al., 2017)
MDO	3.7 (t/t)	(Jochemsen-Verstraeten et al., 2016)	Calculated for dredging	3.5 (t/t)	(Schmied & Knörr, 2012)
Concrete mortar C35/45 (CEMIII)	0.06 (t/t)	NMD	From database DuboCalc	0.04 - 0.57 (t/t)	(Bijleveld et al., 2013)

The next limitation is present in the determination of the current state. The input data for the quay wall was based on an internal reports of the PoR and reports of contracted third parties. During the research however, it was concluded that input data was wrong due to mistakes in the reports. This is noticeable in the DuboCalc research. It was the intention to use the same input data for the consultants as for the case study. However, the input data was changed due to these mistakes, and the input for the DuboCalc review is not a representation of the case study anymore. Although the author tried to reconstruct the same quay wall as in the case study, it cannot be excluded that a part of the data can vary with the actual situation. In addition, it was determined to not include the anchorages piles into the design as it could not be objectified in DuboCalc. It is expected that this will have a (small) negative influence on the total emission.

The case study is an example of the standard 100 meter short sea quay wall. Nonetheless it is a case study and the exercise does consist of project-specific criteria. The transport distance of the excavation and back filling of soil is relatively short, as it was on the project location itself. The amount of excavated material is location depended as well. Knowing that the back filling and excavation are not the largest contributors to the emission (respectively 1 % and 3 %), it is assumed by the author that the input data represents a 100 meter standard quay wall adequately. It should be noted that if the emission of the 100 m quay wall is going to be used in calculations, the considered quay wall is best presented for an approx. 500 meter quay wall. It is expected that for calculation to a larger quay wall, the emission per 100 meter will not decrease much. However, for smaller quay walls the emission per 100 meter will increase. This is due to 'Economies of scales'. Especially the emission due to the generators for temporary drainage will increase, because the construction pit will be drained for a relative longer time.

In relation to research question 3

The proposed measures to reduce emissions are all material improvements. The changes in design does show potential, but they are not able to be quantified yet. That is why, this measures are not taken into account further and more research in them is advised. The second anchorage to extend the lifetime of the quay wall is a potential reduction measure as well. However, it will not show reduction, if the evaluation procedure of a life time of 100 years is followed, and therefor not further applied.

As discussed already, the author concludes that the DuboCalc tool is not fully transparent as the data sources aren't always described. In addition, the calculations behind the results are not always comprehensible and can sometimes be disputed. A first example of this is the negative emission of Azobé hardwood. This implies that the use of hardwood is always a better option than no use at all. This is not a realistic assumption. Secondly, the author used the data to make its own calculations to predict the possible reduction in GHG emission. When the results of the initial situation was checked, a deviation of 1.2 % was found (and per object varying from 0 % to 6 %). The author was not able to reduce the source of this deviation. More insight into the calculations made by DuboCalc could have helped.

The next limitation is correctness of the resulting reductions of the intervention measures. The results are not 100 % correct due to the following reasons. First of all, the deviation that occurred during the copying of the DuboCalc calculations will have an influence, although, with 1,2 % this is considered acceptable. Secondly, the processes during the production of materials are all summed up in one value. This means that extraction equipment, transport from extraction location to production location, production equipment, chemical processes and transport from production location to a storage location are all added together. The author could not apply the intervention measures in this fixed value. However, it is assumed that the energy of production and chemical processes are responsible for the largest part of this value.

The reduction possibilities in the steel production is based on a well-known steel producer in Germany. It can be possible that their reduction goals deviate from other suppliers. The author chose this producer because the relevant information was available. In the calculations of green hydrogen and BEVs trucks, it was assumed that they will have no GHG emission anymore. However, it is not likely that this will be the case in reality. Renewable energy production causes GHG emission as well. It was chosen by the author, because relevant information was missing.

It was noted that in the standard quay wall, the amount of used diesel is fixed. However, PoR experts indicate that reduction is possible if the amount of required diesel was calculated for every specific case instead of a standardized value. This is not taken into account further.

In this report, CCS is seen as a reduction of emission. However, this is disputable. The emissions due to materials is not reduced, only the GHG will not enter the atmosphere. By some, this is not regarded as a reduction. However, the author chose to add this option as it is a suitable temporary solution to GHG reduction, especially for processes that are not able to be reduced further. In this report, the use of renewable energy for ICCP is advised to reduce GHG emission. The PoR office already uses renewable energy. Be that as it may, the connection of ICCP is in reality made by the third party who leases the quay wall. This is project specific and these companies should be encouraged to use renewable energy or the PoR should provide the electricity itself. It may be possible that some companies already have such a contract, but this is not known.

In general

During the use of the tool DuboCalc and the related databases, the author has experienced contradictory circumstances. The tool DuboCalc is designed to quantify projects and to give a reference value with which the contractors can work. In tender procedures, they are challenged to reduce this value as much as possible and uses their own LCA of materials and actions. However, this data is not shared with the NMD database, as it is regarded as company information with competitive value, used to obtain a contract for a specific project although database was intentionally set up so contractors would add data, hence having an up-to-date database. This is not the case now and authorities work with outdated data. The given advice to the authorities to make their own LCA is expected to be repeated work (as the data probably already exists) and may have considerable costs. This money could have been better used to invest in materials and research to actually decrease the emission instead of receiving already present information.

In general, the elaborated intervention measures have a certain uncertainty. The 2050 situation is a long shot and the reports that were consulted, only provide a sketch of what the future will bring. Although the reports were written by experts from various fields, it can not be said that the sketched scenarios will eventually happen. The solutions in material designs are highly dependent on the technical feasibility (generation of green hydrogen), the economically availability (generation of cheap green hydrogen) and the political feasibility (CCS). The author is aware of these uncertainties, but tried to show the most likely development path.

The author wants to discuss the impact of quay wall development on the total GHG emission in the PoR. As described in Chapter 3, the emission of the port industrial complex is equal to 30 Mt in 2015/2016. The PoR project are around 0.1-0.2 Mt. This is approx. 0.5 % of the emission in the PoR itself. It is a considerable small part of the total sum, but a part that the Port authority can influence strongly. The author is convinced that every small step will help to reduce the GHG emission in total. In addition, the author considers that the PoR should act as an example to fight climate change. The commercial policy of the Port Authority is to make the energy transition take place in the Rotterdam area, then the Port authority should try to be the 'launching customer' for fuels and materials that help to make this transition happen. Research that has been done for the PoR could be important for various actors, from technical consultants, contractors and suppliers of materials. All parties should act to reduce GHG emission in port development. However, the emission of the companies located in the PoR, should be in line with the emission of PoR projects. This way, reduction in emission of projects is not compensated by other companies.

Finally, this report focuses on GHG emission. This was one of the operational objectives (targets) of the aspect of sustainability 'Air pollutants'. Improving the reduction of GHG emission, in many cases also improves the air quality. However, focusing only on GHG emission could lead to unwanted side effects. If the GHG emission is reduced, doesn't automatically mean that the other targets that fall under air pollutants are improved as well. In total, it would not automatically mean that the air quality improves. In addition, GHG-reducing intervention measures could also impact other aspects of sustainability. An example of this is the use of hardwood Azobé. Deforestation will impact aspects like the biological ecosystem. This is not taken into account in this report, however it is of most important that a solution is always weighted against the negative impacts on the other aspects.

7.2. Conclusion

In this Paragraph, the three research questions that were set-up in Chapter 1, will be answered on the basis of the results of the research.

Research question 1

Question:

How can the sustainable performance of a quay wall during the full life cycle be objectively assessed?

The sustainability performance of a quay wall during the full life cycle can be assessed by applying the Framework of Sustainable Port Infrastructure (FoSPI), which is based on the Frame of Reference method. The FoSPI is developed in this research and it consists of fourteen sustainability aspects that are generally applicable for all types of port infrastructure assets. Each aspects includes one of more targets that are determined by the company and/or by its location's regulations. Furthermore each target requires a quantification tool, a reference base, intervention measures and an evaluation procedure. These depend on the location and the type of infrastructure asset. If the target(s) is (are) achieved, this would mean that the infrastructure has reached a more sustainable level on this aspect. All fourteen aspects should meet their target(s) to conclude that the infrastructure has reached a more sustainable level.

The FoSPI is applied to quay wall development in the PoR and it is found that only four out of fourteen aspects are fully specified and therefore can be assessed. It was not possible to assess the other aspects due to a missing quantification tool, current state, intervention measures and/or evaluation procedure. To assess the quay wall in total, the remaining eleven aspects should be defined and investigated further. It can be concluded that it is not possible to assess a quay wall at the moment on all aspects of the FoSPI.

The research has further been focused on a prioritized aspect for the PoR. This aspect was determined using literature and interviews with PoR personnel. The choice was made to focus on the GHG emission of the aspect 'Air pollutants' in quay wall development. For this aspect, the quantification tool, a reference state, intervention measures and an evaluation procedure, specified for a quay wall, were not defined yet.

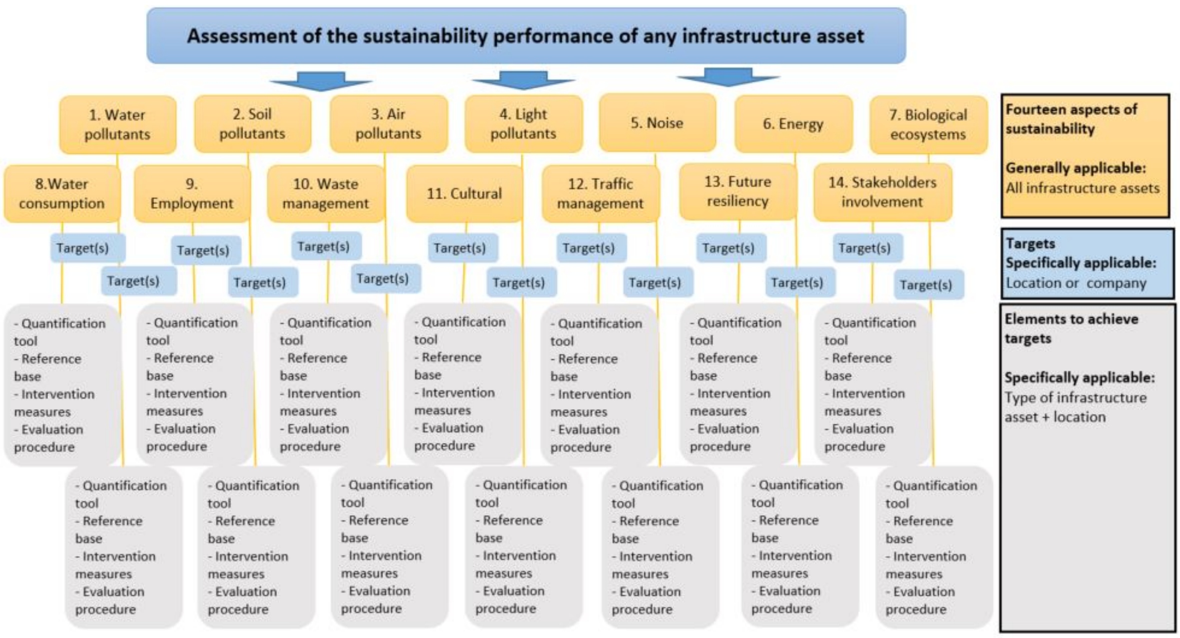


Figure 7.1: The blank Framework of Sustainable Port Infrastructure (FoSPI), based on the Frame of Reference method.

Research question 2
Question:

Based on the selected method in research question 1, what is the sustainability performance of a quay wall in the Port of Rotterdam?

The sustainability performance prioritized on GHG emission, of a 100 meter PoR standard short sea quay wall with a life cycle of 100 years is estimated at 1.9 kt CO_2-eq. The largest contributors are steel (rebar, sheet piles and steel piles), electricity (ICCP), fuel (temporary drainage and dredging) and concrete (mortar). This can be seen in Figure 7.2.

DuboCalc is used to quantify GHG emission as it is a sector-specific tool (it contains various pre-designed infrastructure objects) and it relatively simple (compared to other quantification tools), which leads to time and costs savings. However, the tool should be handled with a certain caution. The research showed that the results of a calculation of the GHG emission of a standardised quay wall, are not 100 % reproducible. However, when a thorough check and evaluation is part of the process, the results will converge. In the research, the results of the exercise had a relative range of 28 %, but after a thorough check and evaluation, the second results achieved a range of 8 %. Secondly, it doesn't include all quay wall objects yet and some data is not up-to-date, hence it will give an approximately GHG emission.

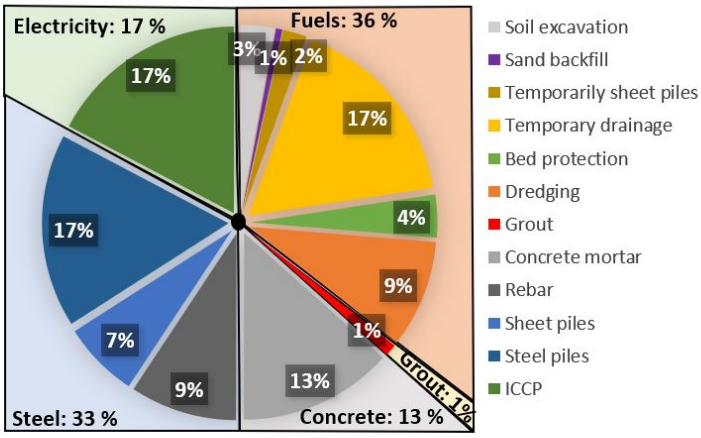


Figure 7.2: Results of the case study expressed in percentages

Research question 3
Question:

How can the Port of Rotterdam achieve their sustainability targets related to quay wall projects?

The PoR should focus on the largest contributors of GHG emission. The following actions are advised:

- As from 2020, renewable energy could be used for the Impressed Current Cathodic Protection (ICCP) which could lead to a reduction of 15 %. The transition from fossil electricity to renewable electricity is without extra investment costs.
- Secondly, using renewable energy instead of diesel for the temporary drainage systems will reduce the emission with 14 %. Including previous actions a total reduction of 29 % is achieved. The costs of the amount of renewable electricity is lower than the required amount of diesel.
- Thirdly, if the PoR will invest approx. 170 euro for every saved CO_2-eq, Hydrotreated Vegetable Oil (HVO) can be used as an alternative fuel for dredging to reduce emission with 8 %. Including previous actions a total reduction of 37 % is achieved.
- Further research could be done in alternative designs. This could lead to a reduction in concrete and steel use, as they are the larger contributors. Alternative designs includes quay walls made out of Recycled

High Density PolyEthylene (RE-HDPE), smaller dimensions of steel piles and prefab concrete quay walls with geo-polymer-based-cements.

- The evaluation procedure in which the quay wall is monitored every five years, could be implemented. This will help to evaluate the applied intervention measures and to oversee if the targets are going to be achieved. It will be part of the strategical planning of the PoR.
- Furthermore, the PoR could encourage the contractors to use electrified transport (on commercial scale around 2025) and machinery (on commercial scale around 2030) to reduce emission with 3 % and 11 % respectively. Including previous actions a total reduction of 51 % is achieved.
- Finally, anticipate long term technical innovation in concrete with Carbon Capture and Storage (CCS) (on commercial scale around 2030), hydrogen as dredging fuel (on commercial scale around 2050) and steel with hydrogen as reduction-agent (on commercial scale around 2050). This could reduce emission with 9%, 10 % and 24 % respectively. Including previous actions, except use of HVO, a total reduction of 86 % is achieved.

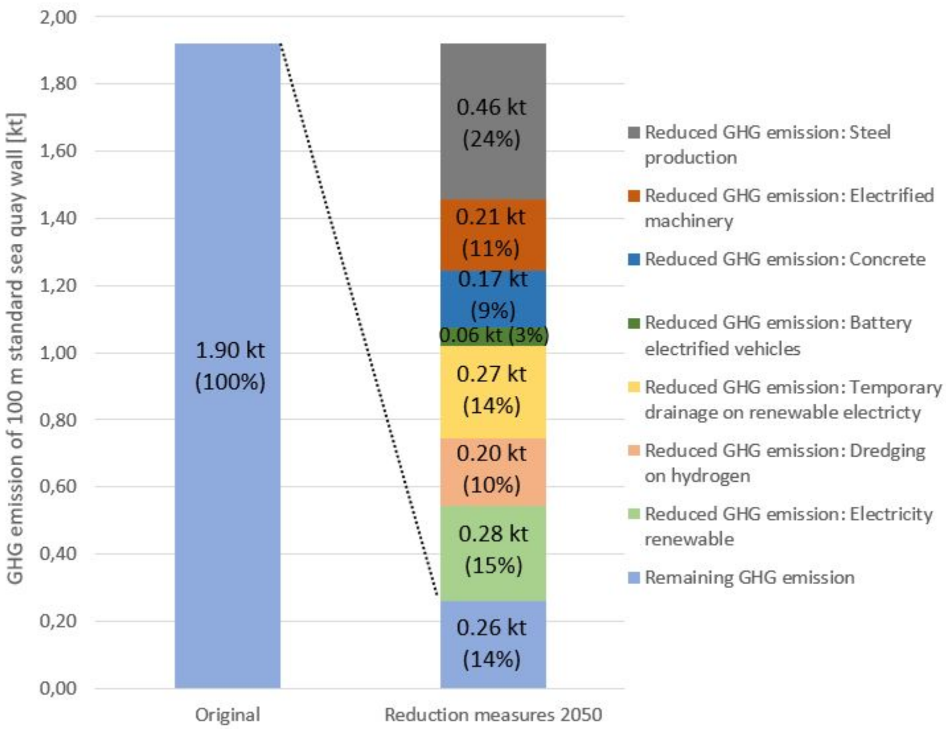


Figure 7.3: Possible reduction scenario in 2050

Although the calculated reduction of GHG emission in 2050 does not satisfy the target of being climate neutral in 2050, the potential reduction of 86 % is a considerable improvement.

For the PoR case, the described three-step approach has led to an improved insight in sustainability of quay wall development, and to concrete recommendations to reduce the GHG emission. The method is applied to quay walls and to the PoR, but it can be applied generally as well, provided that the targets are adapted to the concerned company and its location, and the quantification tool, the reference base and the intervention measures are adapted to the type of asset and the location. The research does contain various limitations (see Paragraph 7.1) and the following recommendations are made.

7.3. Recommendations

In this report, the FoSPI has been applied to quay walls in the PoR. This was an initial determination. However, only the target of GHG emission has been further specified. It is recommended to assess all fourteen aspects the same way as the specified one to be able to assess quay wall projects on all aspects of sustainability, that were determined as relevant. Furthermore, if all aspect can be assessed, it is important that intervention measures that improve one aspect, are weighted against the impacts on the other aspects. This should not have a negative impact. The author propose to use a weighting system that is at least on European scale. This will result in a wide range score that can be compared to other alternatives. However, this could lead to a focus on this score without knowing what it actually means. The existing specific targets should be included, and achieved as well.

In the first results of DuboCalc, a range of 28.60 % was found. After discussion and evaluation of the results, the second results showed a range of 8.26 %. To improve the reproducibility of DuboCalc, evaluating and discussing the results with the consultants should be part of process, as is decreases the range.

Secondly, the objects 'Soil excavation', the anchorage piles 'Anchorage' and the 'Dredging' are not coherently chosen. For the 'Soil excavation' and 'Dredging', there are various applicable objects. The experts are biased i.e. they prefer one object over the other object. It is recommended to choose an preferred object for 'Soil excavation' and 'Dredging' and make clear to the expert to use that object. It is recommended to quantify the emission due to dredging using the object 'MDO' and not the cubic meters of material for dredging. This is due to the large variety of parameters that can be changed during dredging which influences the amount of fuel. This can be the sailing speed of the ship, the weather conditions, the depth of dredged material etc. It is recommended to use 'MDO' for further assessments. The anchorage piles are not represented well, which cause the choice of alternative objects, where others neglect it. For the anchorage piles, a new object should be calculated through a LCA to include this object in the tool.

To improve the representation of DuboCalc, it is advised to make a new LCA of the large contributors of the total emission. They all consist of a fine of 30 % (category 3), which implies an uncertainty. Furthermore, the dimensions of the objects are not corresponding with the used objects in the PoR. The input data of ICCP was only based on the usage of electricity. However, this is expected to be an oversimplification of the reality. The coating (existing of extraordinary materials like titanium) and installation necessary for this are not taken into account as the data is not fully known. This is expected to have an negative influence on the results. A detailed LCA of the ICCP is advised. list of LCA.

The answer of research question 3 consists of solutions in which the transition of fossil fuel to renewable electricity is made. These are measures that can be taken now. The difficulty is that an electrical connection needs to be present in the construction phase. For brownland construction sites, a connection could be available as the previous activities on the quay wall require electricity. However, greenfield construction sites doesn't have such a connection, although this will most likely be required over the years. This means that the construction planning and facilitation should be changed. It is recommended to make an electricity connection to the construction location available at the start of the construction phase. It is advised to investigate how to implement this in the planning of construction projects.

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A

The aspects of sustainability

A.1. In and outflow charts in port infrastructure projects (Sotiriadou, 2019)

Table A.1: The in and out flows of sustainable port infrastructure (1). Source: (Sotiriadou, 2019)

Phase	Category	Producer/ receiver	Flow type	Flow type	Main component	System
Design	Material processing	Chemical processes	Effluent gasses	Out	NOx, Sox, Cox, PM, VOC ,HC, odors, others	Air quality
Design	Material processing	Industrial processes	Water	Out	Water	Water consumption
Design	All equipment	Engines	Combustion gases	Out	NOx, Sox, Cox, PM, VOC ,HC, odors, others	Air quality
Design	all activities	Various	Dust - loose materials	Out	Particle matter	Air quality
Design	all activities	Various	Dust - loose materials	Out	Particle matters - other materials	Water quality
Design	all activities	Various	Dust - loos materials	Out	Particle matters - other materials	Soil quality
Design	all activities	Various	Dust - loose materials / light	Out	Particle matters - other materials / photons	Light
Design	All activities	Engines, movements, beepers, etc.	Noise	Out	Sound waves	Acoustic
Design	All equipment	Engines, hydraulic systems, others	Oily waste	Out	Oily materials	Waste
Design	all activities	Various	Garbage	Out	Various ; separated flows	Waste
Design	all activities	Various	other waste	Out	Various ; separated flows	Waste
Design	all activities	Engines	Fuel	In	Petrol;diesel;LNG ; others	Depletion
Design	All equipment	Various	Maintenance materials / spare parts	In	Various	Depletion
Design	all activities	various	Non- hazardous demolition materials	Out	Various	Waste
Design	All equipment	Various	Electricity supply	In	Electricity	Energy consumption

Table A.2: The in and out flows of sustainable port infrastructure (2). Source: (Sotiriadou, 2019)

Phase	Category	Producer/ receiver	Flow type	Flow type	Main component	System
Construction	All equipment	Engines	Combustion gases	Out	NOx, Sox, Cox, PM, VOC ,HC, odors, others	Air quality
Construction	all activities	Various	Dust - loose materials	Out	Particle matter	Air quality
Construction	all activities	Various	Dust - loose materials	Out	Particle matters - other materials	Water quality
Construction	all activities	Various	Dust - loos materials	Out	Particle matters - other materials	Soil quality
Construction	all activities	Various	Dust - loose materials / light	Out	Particle matters - other materials / photons	Light
Construction	All activities	Engines, movements, beepers, etc.	Noise	Out	Sound waves	Acoustic
Construction	All equipment	Engines, hydraulic systems, others	Oily waste	Out	Oily materials	Waste
Construction	all activities	Various	Garbage	Out	Various ; separated flows	Waste
Construction	all activities	Various	other waste	Out	Various ; separated flows	Waste
Construction	all activities	Engines	Fuel	In	Petrol;diesel;LNG ; others	Depletion
Construction	All equipment	Various	Maintenance materials / spare parts	In	Various	Depletion
Construction	all activities	various	Construction materials	In	Various	Depletion
Construction	all activities	various	Non- hazardous demolition materials	Out	Various	Waste
Construction	All equipment	Various	Electricity supply	In	Electricity	Energy consumption
Construction	Employment	Construction operations	Word demand	In	Personnel	Labor safety
Construction	Marine activities	Various	Underwater noise	Out	Sound waves	Acoustic
Construction	Marine activities	Various	Sediment resuspension and transport	Out	Various sediments components	Water quality
Construction	Marine activities	Various	Sediment resuspension and transport	Out	Various sediments components/photons	Light
Construction	Dredging	Port basin	Dredging operations	Out	Physical damage	Ecosystems
Construction	Dredging	Port basin	Dredging operations	Out	Resuspension of sediments	Water quality
Construction	Dredging	Port basin	Dredging material disposal	Out	Hazardous materials	Waste
Construction	Dredging	Port basin	Dredging material disposal	Out	Non - hazardous materials	Waste
Construction	Dredging	Port basin	Dredging material open sea dumping	Out	Physical damage	Ecosystems
Construction	Dredging	Port basin	Dredging material open sea dumping	Out	Non - hazardous materials	Soil - sediments
Construction	Transport	Connection network	Quantity of vehicles	Out	Cultural	

Table A.3: The in and out flows of sustainable port infrastructure (3). Source: (Sotiriadou, 2019)

Phase	Category	Producer/ receiver	Flow type	Flow type	Main component	System
Maintenance	All equipment	Engines	Combustion gases	Out	NOx, Sox, Cox, PM, VOC ,HC, odors, others	Air quality
Maintenance	all activities	Various	Dust - loose materials	Out	Particle matter	Air quality
Maintenance	Biodiversity	Plants, organisms	Absorption of gases and metals	Out	NOx, Sox, Cox, PM, VOC ,HC, metals	Water quality
Maintenance	all activities	Various	Dust - loose materials	Out	Particle matters - other materials	Water quality
Maintenance	all activities	Various	Dust - loos materials	Out	Particle matters - other materials	Soil quality
Maintenance	all activities	Various	Dust - loose materials / light	Out	Particle matters - other materials / photons	Light
Maintenance	All activities	Engines, movements, beepers, etc.	Noise	Out	Sound waves	Acoustic
Maintenance	All equipment	Engines, hydraulic systems, others	Oily waste	Out	Oily materials	Waste
Maintenance	all activities	Various	Garbage	Out	Various ; separated flows	Waste
Maintenance	all activities	Various	other waste	Out	Various ; separated flows	Waste
Maintenance	all activities	Engines	Fuel	In	Petrol;diesel;LNG ; others	Depletion
Maintenance	All equipment	Various	Maintenance materials / spare parts	In	Various	Depletion
Maintenance	all activities	various	Construction materials	In	Various	Depletion
Maintenance	all activities	various	Non- hazardous demolition materials	Out	Various	Waste
Maintenance	All equipment	Various	Electricity supply	In	Electricity	Energy consumption
Maintenance	Employment	Construction operations	Word demand	In	Personnel	Labor safety
Maintenance	Marine activities	Various	Underwater noise	Out	Sound waves	Acoustic
Maintenance	Marine activities	Various	Sediment resuspension and transport	Out	Various sediments components	Water quality
Maintenance	Marine activities	Various	Sediment resuspension and transport	Out	Various sediments components/photons	Light
Maintenance	Dredging	Port basin	Dredging operations	Out	Physical damage	Ecosystems
Maintenance	Dredging	Port basin	Dredging operations	Out	Resuspension of sediments	Water quality
Maintenance	Dredging	Port basin	Dredging material disposal	Out	Hazardous materials	Waste
Maintenance	Dredging	Port basin	Dredging material disposal	Out	Non - hazardous materials	Waste
Maintenance	Dredging	Port basin	Dredging material open sea dumping	Out	Physical damage	Ecosystems
Maintenance	Dredging	Port basin	Dredging material open sea dumping	Out	Non - hazardous materials	Soil - sediments
Maintenance	All material	Leaks of materials	Metals, pH change	Out	Metals, basis	Water quality

Table A.4: The in and out flows of sustainable port infrastructure (4). Source: (Sotiriadou, 2019)

Phase	Category	Producer/ receiver	Flow type	Flow type	Main component	System
End-of-life	all activities	various	Hazardous demolition materials	Out	Various	Waste
End-of-life	All equipment	Engines	Combustion gases	Out	NOx, Sox, Cox, PM, VOC ,HC, odors, others	Air quality
End-of-life	all activities	Various	Dust - loose materials	Out	Particle matter	Air quality
End-of-life	all activities	Various	Dust - loose materials	Out	Particle matters - other materials	Water quality
End-of-life	all activities	Various	Dust - loos materials	Out	Particle matters - other materials	Soil quality
End-of-life	all activities	Various	Dust - loose materials / light	Out	Particle matters - other materials / photons	Light
End-of-life	All activities	Engines, movements, beepers, etc.	Noise	Out	Sound waves	Acoustic
End-of-life	All equipment	Engines, hydraulic systems, others	Oily waste	Out	Oily materials	Waste
End-of-life	all activities	Various	Garbage	Out	Various ; separated flows	Waste
End-of-life	all activities	Various	other waste	Out	Various ; separated flows	Waste
End-of-life	all activities	Engines	Fuel	In	Petrol;diesel;LNG ; others	Depletion
End-of-life	All equipment	Various	Maintenance materials / spare parts	In	Various	Depletion
End-of-life	all activities	various	Construction materials	In	Various	Depletion
End-of-life	all activities	various	Non- hazardous demolition materials	Out	Various	Waste
End-of-life	All equipment	Various	Electricity supply	In	Electricity	Energy consumption
End-of-life	Employment	Construction operations	Word demand	In	Personnel	Labor safety
End-of-life	Marine activities	Various	Underwater noise	Out	Sound waves	Acoustic
End-of-life	Marine activities	Various	Sediment resuspension and transport	Out	Various sediments components	Water quality
End-of-life	Marine activities	Various	Sediment resuspension and transport	Out	Various sediments components/photons	Light
End-of-life	Dredging	Port basin	Dredging operations	Out	Physical damage	Ecosystems
End-of-life	Dredging	Port basin	Dredging operations	Out	Resuspension of sediments	Water quality
End-of-life	Dredging	Port basin	Dredging material disposal	Out	Hazardous materials	Waste
End-of-life	Dredging	Port basin	Dredging material disposal	Out	Non - hazardous materials	Waste
End-of-life	Dredging	Port basin	Dredging material open sea dumping	Out	Physical damage	Ecosystems
End-of-life	Dredging	Port basin	Dredging material open sea dumping	Out	Non - hazardous materials	Soil - sediments

A.2. Existing sustainability guidelines

A.2.1. United Nations Sustainability Development Goals.

Figure A.1: United Nations Sustainability Development Goals. Source: (United Nations, 2018)

A.2.2. International Finance Corporation

Table A.5: The Performance Standards of the International Finance Corporation. Source: (World Bank Group, 2017b)

Performance standard	Criteria
PS 1	Social and Environmental Assessment and Management Systems
PS 2	Labour and Working Conditions
PS 3	Pollution Prevention and Abatement
PS 4	Community Health, Safety and Security
PS 5	Land Acquisition and Involuntary Resettlement
PS 6	Biodiversity Conservation and Sustainable Natural Resource Management
PS 7	Indigenous People
PS 8	Cultural Heritage

Table A.6: The Environmental, Health, and Safety Guidelines of the International Finance Corporation for port, harbors and terminal industry. Source: (World Bank Group, 2017b)

EHS Issues	**Criteria**
EHS 1.1	Terrestrial and aquatic habitat alteration and biodiversity
EHS 2.2	Climate change resilience
EHS 1.3	Water quality
EHS 1.4	Air emissions
EHS 1.5	Waste management
EHS 1.6	Hazardous materials and oil management
EHS 1.7	Noise and vibration (including underwater)
EHS 2.1	Physical hazards
EHS 2.2	Chemical hazards
EHS 2.3	Confined spaces
EHS 2.4	Exposure to organic and inorganic dust
EHS 2.5	Exposure to noise
EHS 3.1	Port marine safety
EHS 3.2	Port security
EHS 3.3	Visual impact

A.2.3. BREEAM

Sections	Criteria	Further explanation
Management	MAN 1 Commissioning	Stimulating a good way of securing performance of installations, so optimum performance under normal conditions is assured.
	MAN 2 Construction site and surroundings	Encouraging the responsible management of the site and its impact on the environment.
	MAN 3 Construction site impact	Encouraging environmentally responsible site management in terms of environmentally conscious materials, reduce energy consumption and reduce pollution.
	MAN 4 User guide	To encourage the provision of a building manual for non-technical users of the building to enable them to understand the building and efficiently to deal with
	MAN 6 Consultation	The involvement of relevant stakeholders (including building users, businesses, residents and local government) in the design process to increase local involvement and to obtain a building that is best suited for its function.
	MAN 8 Security	Identifying and promoting effective design measures in vicinity of the project to increase public safety by offering protection against common crime (such as vandalism, occasion burglaries, theft, etc.).
	MAN 9 The development as a learning source	Stimulation of informing users and visitors about sustainable construction
	MAN 11 Ease of maintenance	Encouraging the design of a building and of (building) installations that can be maintained in a simple manner throughout their life cycle
	MAN 12 Life cycle costing	Encouraging a life cycle cost analysis is performed during the design phase, so that the design and implementation over the lifecycle of the building, including maintenance and management are optimized.
Health	HEA 1 Daylighting	Providing adequate daylighting in residential areas and accommodation areas for the benefit of adequate visual performance and well-being
	HEA 2 View out	Encouraging to ensure that relevant workplaces in occupied areas have an unobstructed view. This to benefit visual comfort and to provide a break to a monotonous indoor environment.
	HEA 3 Glare control	The prevention of nuisance within accommodation areas due to reflection or glare from incident light by the application of blinds etc.
	HEA 4 High frequency lighting	Increase the visual comfort through the use of high-frequency lighting in the usable floor area of a building.
	HEA 5 Internal and external lightning levels	Ensure that the existing artificial lighting ensures a high level of visual comfort for both indoor and outdoor spaces
	HEA 6 Lightning zone and controls	Ensure that the building users have a simple and accessible way to operate the lighting within each space in a building where work takes place.
	HEA 7 Natural ventilation	An additional possibility for the users to (temporarily) vent, directly to the outside air in addition to the basic ventilation in the building.
	HEA 8 Internal air quality	To recognize and encourage a healthy internal environment through the specification and installation of appropriate ventilation
	HEA 9 Volatile organic compounds	Promoting a healthy and good indoor air quality because the used building- and finishing materials cause a low emission of harmful volatile organic compounds and other harmful substances
	HEA 10 Thermal comfort	Ensure a good thermal comfort.
	HEA 11 Thermal zoning	Providing ample opportunity for temperature control (heating and cooling) within usable floor areas by individual building users

	HEA 13 Acoustic Performance	A good sound insulation and soundproofing to prevent as much as possible of noise irritation and noise pollution within a building. And if necessary to reduce this to an acceptable level, to achieve a high degree of acoustic comfort inside the building.
	HEA 14 Private outdoor space	Improve the living standards of residents by providing some privacy in an outdoor area.
	HEA 15 Accessibility	Encouraging that housing and residential buildings are useful for as many possible audiences. This also contributes to making residences lifecycle proof and anticipates the trends of aging.
Energy	ENE 1 Reduction of CO2 emission	Encouraging that buildings are designed and realized with the lowest possible CO2 emissions of the building-related primary energy consumption in the use phase.
	ENE 2a/b Sub- metering of energy uses – (non) residential	Applying sub measurement of both areas within the building as well as significant consumption groups, so that during the use phase, energy use can be recorded, monitored and can be adjusted if necessary by use of a energy monitoring - or building management system.
	ENE 4 Energy-efficient external lightning	Stimulating energy saving and CO 2 reduction through the application of energy-efficient outdoor lighting
	ENE 5 Use of renewable energy	Promote the use of renewable energy in the immediate vicinity.
	ENE 6 Building fabric performance and avoidance of air filtration	Stimulating energy saving and CO 2 reduction through the application and design of loading platforms and / or expedition areas with a minimum loss of heat or cold.
	ENE 7a/b Energy efficient refrigerated and frozen storage – all	Stimulating energy saving and CO 2 reduction through the use of energy-efficient storage facilities where products are kept refrigerated or frozen.
	ENE 8 Energy efficient lifts	Stimulating energy saving and CO 2 reduction by applying energy-efficient elevators that are attuned to the usage.
	ENE 9 Energy efficient escalators and travellators	Stimulating energy saving and CO 2 reduction through the use of energy-efficient escalators and moving walkways.
	ENE 26 Assurance of thermal quality of building	Encouraging that buildings are constructed as designed and realized with the lowest possible CO2 emissions.
Transport	TRA 1a/b/c Provision of public transport - all	Recognizing and encouraging developments of a good public transport network in the vicinity, by which transport-related emissions and traffic jams are reduced.
	TRA 2 Proximity to amenities	Recognizing and encouraging developments in close proximity to local amenities which transport related emissions and traffic jams are reduced.
	TRA 3a/b Alternative modes of transport – (non) residential	Encouraging building users to make use alternative transportation, other than the private car, to and from the building
	TRA 4 Pedestrians and cyclist safety	Stimulating the presence of available safe pedestrian and bicycle access routes to the site.
	TRA 5 Travel plan and parking policy	Incentives from building operations and local government to minimize strong environmental impact through which transport-related emissions and traffic jams are reduced and nuisance to the environment is limited.
	TRA 7 Travel information point	Ensure that the building has the capacity to provide users of up to date information regarding current local public transport routes and times.
	TRA 8 Deliveries and maneuvering	Ensure that safety is maintained and disruption of access by delivery traffic is minimized by good design and safe access to the area.
Water	WAT 1a/b Water consumption – (non) residential	The minimizing of water use for sanitary applications by the use of water-saving and water-free facilities.
	WAT 2 Water meter	Ensure that water consumption can be monitored and managed. This will stimulate the reduction of the drinking water and ground water consumption.
	WAT 3 Major leak detection	Limiting the consequences of major water leaks that would otherwise remain undetected

	WAT 4 Sanitary supply shut off	The reduction of water loss due to small water leakages in toilet facilities.
	WAT 5 Water recycling	For flushing toilets stimulate the use of capture and reuse of gray water or rainwater and reduce the use of drinking water.
	WAT 6 Irrigation systems	Reduce the use of drinking water for landscaping.
	WAT 7 Vehicle wash	Reduction of water consumption by minimizing vehicles washes.
Materials	MAT 1 Materials specifications	Identifying and encouraging the use of materials with a low environmental impact throughout the lifecycle of the building.
	MAT 5 Responsible sourcing of materials	Encouraging the use of materials with a proven/sound source in the main components.
	MAT 7 Designing for robustness	Identifying and promoting measures to protect exposed parts of the building and site design, ensuring the replacement frequency is minimized.
	MAT 8 Building flexibility	The stimulation of the development of buildings with a high degree of flexibility.
Waste	WST 1 Waste management on the construction site	Maximize resources by promoting meaningful and effective waste management on site.
	WST 2 Recycled aggregates	To recognize and encourage the use of recycled and secondary aggregates, thereby reducing the demand for virgin material and optimizing material efficiency in construction.
	WST 3a/b Recyclable waste storage – (non) residential	The designation of facilities used specifically for the storage of recyclable waste during the operation / use of the building, so efficiently separating recyclable waste is encouraged.
	WST 5 Compost	Stimulating facilities for composting of organic waste, to reduce the amount of organic waste or to make suitable for use on site
	WST 6 Finishing elements	Promoting coordination with the future building users about the furnishings to be used and design of the building and thereby avoided waste of material.
Land use and ecology	LE 1 Re use of land	To encourage project developers, municipalities, housing corporations and other constructing parties to realize building projects at locations with a low ecological and landscape value, and to encourage the reuse of previously developed land in order to prevent the unregulated proliferation of buildings in rural areas
	LE 2 Contaminated land	The realization of construction projects in locations with contaminated soil rather than in locations with clean soil.
	LE 3 Existing wildlife at the construction site	To encourage the adoption of measures to protect and maintain plants and animals that are present on the site during construction.
	LE 4 Plants and animals as co-users of the plan area	Encouraging the adoption of design measures for the sustainable shared use of the to develop building and open space by native plant and animal species.
	LE 6 Long – term sustainable co-use by plants and animals	Encouraging environmentally friendly management, maintenance and wildlife monitoring of the building and open space, to ensure sustainable shared use of the plants and animals targeted under 3 LE and LE 4.
	LE 9 Efficient land use	Promoting efficient land use by limiting the built area within the development.
Pollution	POL 1 Refrigerated GWP – Building services	To contribute to a reduction in national NOx emission levels through the use of low emission heat sources in the building.
	POL 2 Preventing refrigerated leaks	Preventing emissions of refrigerants into the atmosphere, caused by leaks in refrigeration (for air conditioning and refrigeration of goods).

Figure A.4: BREEAM (3). Source: (BREEAM, 2014)

	POL 3 Refrigerated GWP – Cold storage	Reduce the contribution to climate change by encouraging the use of refrigerants with a low contribution to the greenhouse effect
	POL 4 NOx emissions from heating sources	Stimulating the application of heat system in which the NOx emission is minimized. This will reduce local air pollution.
	POL 6 Surface water run -off	To avoid, reduce and delay the discharge of rainfall to public sewers and watercourses, therefore minimizing the risk of localized flooding on and off site, watercourse pollution and other environmental damage
	POL 7 Reduction of night time light pollution	Ensure that outdoor lighting is arranged in such a way that the right areas are illuminated, light facing up is minimized and light pollution, energy consumption and nuisance to adjacent lots is minimized.
	POL 8 Noise attenuation	Reducing the chance that sound of the project constitutes nuisance for nearby noise sensitive buildings during the use phase.

Figure A.5: BREEAM (4). Source: (BREEAM, 2014)

A.2.4. CEEQUAL

Table A.7: Table with CEEQUAL criteria for sustainability. Source: (CEEQUAL, 2019)

Sections	Criteria
1. Project / contract strategy	1. Evidence of client and designers have undertaken principles of sustainability
2. Project / Contract management	1. Environmental management practices 2. Social issues in developing, designing and constructing phase 3. Training
3. People and communities	1. Minimizing operation- and construction-related nuisances 2. Legal requirements 3. Community consultation 4. Community relations programs and their effectiveness 5. Engagement with relevant local groups 6. Human environment, aesthetics and employment
4. Land use and landscape	1. Design for optimum land-take 2. Legal requirements 3. Flood risks 4. Previous use of the site 5. Land contamination 6. Remediation measures 7. Conventional land use 8. Use of sea, estuaries, rivers and lakes 9. Landscape design 10. Landscape amenity features 11. Landscape local character 12. Loss and compensation or mitigation features 13. Implementation and management 14. Completion and aftercare
5. Historic Environment	1. Conservation and enhancement measure 2. Information and public access
6. Ecology and Biodiversity	1. Habitat creation measures 2. Habitat monitoring 3. Habitat maintenance 4. Protected species 5. Surveys conservations & enhancement 6. Ecological value
7. Water environment	1. Water environment protection 2. Legal requirements 3. Enhancement of water environment
8. Physical resources use and management	1. LCA 2. Energy and carbon emissions in use 3. Energy and carbon performance on site 4. Minimizing use and impacts of hazardous materials 5. Minimizing material use and waste 6. Responsible sourcing of materials incl. timber 7. Using reused /recycled materials 8. Durability and maintenance 9. Future deconstruction or disassembly 10. Design for waste minimization 11. Legal requirements 12. Waste from site preparation 13. Minimizing water consumption and embodied water 14. Policies and targets for resource efficiency 15. On-site waste management
9. Transport	1. Minimizing traffic impacts of a project 2. Construction transport 3. Minimizing workforce travel 4. Access for pedestrian and cyclist 5. Need for add. transport infrastructure arising for the project 6. Resilience of the network 7. Performance for non-motorized users

A.2.5. Ambitieweb

Table A.8: An overview of the criteria of the ambitieweb. Source: (Duurzaam GWW, 2019)

Sustainable topic	**Requirement**
Accessibility	Trustful and robustness
	Efficient infrastructure use
	Accessible functions
	Sustainable mobility
Area quality	Value of experience
	Value of future
Area use	Connection to regional development
	Urbanization and efficient area use
	Multiple area use
Ecology	Habitat diversity and quality
	Rest of flora and fauna
Energy	Energy reduction
	Renewable energy
	Energy saving
Health	Healthy environment
	Save environment
	Physical training
Investment climate	Clusters
	Knowledge infrastructure
Investments	Life cycle costs
	Future proof investments
Materials	Material reduction
	Preservation of value
	Adaptable, maintainable and reusable
	Sustainable materials
Social relevance	Community support and local expertise
	Social exclusivity
Soil	Soil settlement
	Groundwater
	Underground infrastructure
	Archaeological values
	Quality of soil and variation
Water	Water safety
	Reduction of water hindrance
	Water quality
	Extreme weather

A.2.6. Neglected criteria

Neglected indicators		**Reason**
UN SDG's		
1	No poverty	Although poverty could be prevented by choosing material from poor countries, it depends on many factors and it is not directly linked to the life cycle of a quay wall. For that reason it is neglected.
2	No hunger	Although hunger could be prevented by fare trade choosing materials, it depends on many factors and it is not directly linked to the life cycle of a quay wall. For that reason it is neglected.
5	Gender equality	Although working with companies who stand for gender equality, it is not directly linked to the life cycle of a quay wall. For that reason it is neglected.
10	Reduced inequalities	Although working with companies who stand for reduced inequalities, it is not directly linked to the life cycle of a quay wall. For that reason it is neglected.
IFC PS		
PS 5	Land Acquisition and Involuntary Resettlement	Land acquisition is not part of this rapport. Land is already acquired in this case.
IFC EHS		
EHS 3.1	Port marine safety	Operations of the port. Not a part of the life cycle of a quay wall
EHS 3.2	Port security	Operations of the port. Not a part of the life cycle of a quay wall
EHS 3.3	Visual impact	Operations of the port. Not a part of the life cycle of a quay wall
BREEAM		
MAN 1	Commissioning	Absence of installations.
MAN 4	User guide	Absence of building
HEA 1	Daylighting	Absence of indoor spaces
HEA 2	View out	Absence of indoor spaces
HEA 3	Glare control	Absence of accommodation.
HEA 4	High frequency lighting	Absence of indoor spaces
HEA 5	Internal and external lightning levels	Absence of indoor spaces
HEA 6	Lightning zone and controls	Absence of indoor spaces
HEA 7	Natural ventilation	Absence of indoor spaces
HEA 8	Internal air quality	Absence of indoor spaces
HEA 9	Volatile organic compounds	Absence of indoor spaces
HEA 10	Thermal comfort	Absence of indoor spaces
HEA 11	Thermal zoning	Absence of indoor spaces
HEA 13	Acoustic Performance	Absence of indoor spaces

HEA 14	Private outdoor space	No residency
ENE 6	Building fabric performance and avoidance of air filtration	No loading platforms
ENE 7a/b	Energy efficient refrigerated and frozen storage – all	No refrigerated and frozen storage
ENE 8	Energy efficient lifts	No lifts
ENE 9	Energy efficient escalators and travellators	No escalators
ENE 26	Assurance of thermal quality of building	No building
TRA 2	Proximity to amenities	No choice of location
TRA 4	Pedestrians and cyclist safety	Although the entrance of the site should be in line with the safety of the pedestrians and cyclist. Pedestrians and cyclist will not be allowed on the construction site.
WAT 4	Sanitary supply shut off	No definite located toilet facilities
WAT 5	Water recycling	No definite located toilet facilities
WAT 6	Irrigation systems	No landscape
WAT 7	Vehicle wash	No residents
WST 5	Compost	Low amount of organic waste from constructors.
WST 6	Finishing elements	No future building
LE 1	Re use of land	Not part of the life cycle of a quay wall
POL 1	Refrigerated GWP – Building services	No refrigerated and frozen storage
POL 2	Preventing refrigerated leaks	No refrigerated and frozen storage
POL 3	Refrigerated GWP – Cold storage	No refrigerated and frozen storage
Ceequal		
4.8	Use of sea, estuaries, rivers and lakes	Quay walls are always connected to waterbodies, so this criteria doesn't is not important
4.9	Landscape design	Design of landscape is neglected, quay wall is not a landscape.
4.10	Landscape amenity features	In port, landscape amenity are not preferred.

Figure A.6: Neglected criteria

A.2.7. List of criteria for defining sustainability of the life cycle of port infrastructure

Included criteria	
UN SDG's	
3	Good health
4	Quality education
6	Clean water and sanitation
7	Renewable energy
8	Good jobs and economic growth
9	Innovation and infrastructure
11	Sustainable cities and communities
12	Responsible consumption
13	Climate change
14	Life below water
15	Life on land
16	Peace and justice
17	Partnerships for the goals
IFC PS	
PS 1	Social and Environmental Assessment, Management Systems
PS 2	Labor and Working Conditions
PS 3	Pollution Prevention and Abatement
PS 4	Community Health, Safety and Security
PS 6	Biodiversity Conservation and Sustainable Natural Resource Management
PS 7	Indigenous People
PS 8	Cultural Heritage
IFC EHS	
EHS 1.1	Terrestrial and aquatic habitat alteration and biodiversity
EHS 1.2	Climate change resilience
EHS 1.3	Water quality
EHS 1.4	Air emissions
EHS 1.5	Waste management
EHS 1.6	Hazardous materials and oil management
EHS 1.7	Noise and vibration (including underwater)
EHS 2.1	Physical hazards
EHS 2.2	Chemical hazards
EHS 2.3	Confined spaces
EHS 2.4	Exposure to organic and inorganic dust
EHS 2.5	Exposure to noise
BREEAM	
MAN 2	Construction site and surroundings
MAN 3	Construction site impact

MAN 6	Consultation
MAN 8	Security
MAN 9	The development as a learning source
MAN 11	Ease of maintenance
MAN 12	Life cycle costing
HEA 5	Internal and external lightning levels
HEA 6	Lightning zone and controls
HEA 15	Accessibility
ENE 1	Reduction of CO2 emission
ENE 2a/b	Sub- metering of energy uses – (non) residential
ENE 4	Energy-efficient external lightning
ENE 5	Use of renewable energy
TRA 1a/b/c	Provision of public transport - all
TRA 3a/b	Alternative modes of transport – (non) residential
TRA 5	Travel plan and parking policy
TRA 7	Travel information point
TRA 8	Deliveries and maneuvering
WAT 1a/b	Water consumption –(non) residential
WAT 2	Water meter
WAT 3	Major leak detection
MAT 1	Materials specifications
MAT 5	Responsible sourcing of materials
MAT 7	Designing for robustness
MAT 8	Building flexibility
WST 1	Waste management on the construction site
WST 2	Recycled aggregates
WST 3a/b	Recyclable waste storage – (non) residential
LE 2	Contaminated land
LE 3	Existing wildlife at the construction site
LE 4	Plants and animals as co-users of the plan area
LE 6	Long – term sustainable co-use by plants and animals
LE 9	Efficient land use
POL 4	NOx emissions from heating sources
POL 6	Surface water run -off
POL 7	Reduction of night time light pollution
POL 8	Noise attenuation
Ceequal	
1.1	Project / contract strategy: Evidence of client and designers have undertaken principles of sustainability
2.1	Project / Contract management: Environmental management practices
2.2	Project / Contract management: Social issues that arise from developing, designing and constructing the project
2.3	Project / Contract management: Training

3.1	People and communities: Minimizing operation- and construction-related nuisances
3.2	People and communities: Legal requirements
3.3	People and communities: Community consultation
3.4	People and communities: Community relations programs and their effectiveness
3.5	People and communities: Engagement with relevant local groups
3.6	People and communities: Human environment, aesthetics and employment
4.1	Land use and landscape: Design for optimum land-take
4.2	Land use and landscape: Legal requirements
4.3	Land use and landscape: Flood risks
4.4	Land use and landscape: Previous use of the site
4.5	Land use and landscape: Land contamination
4.6	Land use and landscape: Remediation measures
4.7	Land use and landscape: Conventional land use
4.11	Land use and landscape: Landscape local character
4.12	Land use and landscape: Loss and compensation or mitigation features
4.13	Land use and landscape: Implementation and management
4.14	Land use and landscape: Completion and aftercare
5.1	Historic Environment: Conservation and enhancement measure
5.2	Historic Environment: Information and public access
6.1	Ecology and Biodiversity: Habitat creation measures
6.2	Ecology and Biodiversity: Habitat monitoring
6.3	Ecology and Biodiversity: Habitat maintenance
6.4	Ecology and Biodiversity: Protected species
6.5	Ecology and Biodiversity: Surveys conservations & enhancement
6.6	Ecology and Biodiversity: Ecological value
7.1	Water environment : Water environment protection
7.2	Water environment : Legal requirements
7.3	Water environment: Enhancement of water environment
8.1	Physical resources use and management: LCA
8.2	Physical resources use and management: Energy and carbon emissions in use
8.3	Physical resources use and management: Energy and carbon performance on site
8.4	Physical resources use and management: Minimizing use and impacts of hazardous materials
8.5	Physical resources use and management: Minimizing material use and waste
8.6	Physical resources use and management: Responsible sourcing of materials incl. timber
8.7	Physical resources use and management: Using reused /recycled materials
8.8	Physical resources use and management: Durability and maintenance
8.9	Physical resources use and management: Future deconstruction or disassembly
8.10	Physical resources use and management: Design for waste minimization
8.11	Physical resources use and management: Legal requirements
8.12	Physical resources use and management: Waste from site preparation
8.13	Physical resources use and management: Minimizing water consumption and embodied water
8.14	Physical resources use and management: Policies and targets for resource efficiency
8.15	Physical resources use and management: On-site waste management
9.1	Transport: Minimizing traffic impacts of a project

9.2	Transport: Construction transport
9.3	Transport: Minimizing workforce travel
9.4	Transport: Access for pedestrian and cyclist
9.5	Transport: Need for add. transport infrastructure arising for the project
9.6	Transport: Resilience of the network
9.7	Transport: Performance for non-motorized users
Ambitieweb	
1.1	Trustful and robustness
1.2	Efficient infrastructure use
1.3	Accessible functions
1.4	Sustainable mobility
2.1	Value of experience
2.2	Value of future
3.1	Connection to regional development
3.2	Urbanization and efficient area use
3.3	Multiple area use
4.1	Habitat diversity and quality
4.2	Rest of flora and fauna
5.1	Energy reduction
5.2	Renewable energy
5.3	Energy saving
6.1	Healthy environment
6.2	Save environment
6.3	Physical training
7.1	Clusters
7.2	Knowledge infrastructure
8.1	Life cycle costs
8.2	Future proof investments
9.1	Material reduction
9.2	Preservation of value
9.3	Adaptable, maintainable and reusable
9.4	Sustainable materials
10.1	Community support and local expertise
10.2	Social inclusivity
11.1	Soil quality
11.2	Soil system
11.3	Archaeological values
12.1	Water safety
12.2	Reduction of water hindrance
12.3	Water quality
12.4	Extreme weather

Figure A.7: List of criteria for defining sustainability of the life cycle of port infrastructure

A.3. Cross check: determining the aspects of sustainability

	Included criteria	Air quality	Water quality	Soil quality	Water consumption	Noise	Sourcing / Waste	Energy	Light	Ecosystem and habitat	Labor safety	Cultural	Future res	Traffic	Stakehold
JN SDG's															
3	Good health	☑	☑	☑	☐	☑	☑	☐	☑	☑	☑	☐	☐	☐	☐
4	Quality education	☐	☐	☐	☐	☐	☐	☐	☐	☐	☑	☐	☐	☐	☐
6	Clean water and sanitation	☐	☑	☐	☐	☐	☑	☐	☐	☐	☐	☐	☐	☐	☐
7	Renewable energy	☐	☐	☐	☐	☐	☐	☑	☐	☐	☐	☐	☐	☐	☐
8	Good jobs and economic growth	☐	☐	☐	☐	☐	☐	☐	☐	☐	☑	☐	☐	☐	☐
9	Innovation and infrastructure	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☑	☑	☐
11	Sustainable cities and communities	☐	☐	☐	☐	☐	☐	☐	☐	☐	☑	☐	☐	☐	☐
12	Responsible consumption	☐	☐	☐	☑	☐	☑	☑	☐	☐	☐	☐	☐	☐	☐
13	Climate change	☑	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
14	Life below water	☐	☑	☐	☐	☑	☐	☐	☑	☑	☐	☐	☐	☐	☐
15	Life on land	☑	☐	☑	☐	☐	☐	☐	☑	☑	☐	☐	☐	☐	☐
16	Peace an justice	☐	☐	☐	☐	☐	☐	☐	☐	☐	☑	☐	☐	☐	☑
17	Partnerships for the goals	☐	☐	☐	☐	☐	☐	☐	☐	☐	☑	☐	☐	☐	☑
IFC PS															
PS 1	Social and Environmental Assessment, Management Systems	☑	☑	☑	☑	☑	☑	☐	☑	☑	☑	☐	☐	☐	☑
PS 2	Labor and Working Conditions	☐	☐	☐	☐	☐	☐	☐	☐	☐	☑	☐	☐	☐	☐
PS 3	Pollution Prevention and Abatement	☑	☑	☑	☑	☑	☑	☑	☑	☐	☐	☐	☐	☐	☐
PS 4	Community Health, Safety and Security	☑	☑	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
PS 6	Biodiversity Conservation and Sustainable Natural Resource Management	☐	☐	☐	☐	☐	☑	☐	☐	☑	☐	☐	☐	☐	☐
PS 7	Indigenous People	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☑	☐	☐	☐
PS 8	Cultural Heritage	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☑	☐	☐	☐
IFC EHS															
EHS 1.1	Terrestrial and aquatic habitat alteration and biodiversity	☐	☐	☐	☐	☐	☐	☐	☐	☑	☐	☐	☐	☐	☐
EHS 1.2	Climate change resilience	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☑	☐	☐
EHS 1.3	Water quality	☐	☑	☐	☐	☑	☐	☐	☐	☑	☐	☐	☐	☐	☐
EHS 1.4	Air emissions	☑	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
EHS 1.5	Waste management	☐	☐	☐	☐	☐	☑	☐	☐	☐	☐	☐	☐	☐	☐
EHS 1.6	Hazardous materials and oil management	☐	☐	☐	☐	☐	☑	☐	☐	☐	☐	☐	☐	☐	☐
EHS 1.7	Noise and vibration (including underwater)	☐	☐	☐	☐	☑	☐	☐	☐	☐	☐	☐	☐	☐	☐
EHS 2.1	Physical hazards	☐	☐	☐	☐	☐	☐	☐	☐	☐	☑	☐	☐	☐	☐
EHS 2.2	Chemical hazards	☐	☐	☐	☐	☐	☐	☐	☐	☐	☑	☐	☐	☐	☐
EHS 2.3	Confined spaces	☐	☐	☐	☐	☐	☐	☐	☐	☐	☑	☐	☐	☐	☐
EHS 2.4	Exposure to organic and inorganic dust	☑	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
EHS 2.5	Exposure to noise	☐	☐	☐	☐	☑	☐	☐	☐	☐	☐	☐	☐	☐	☐
BREEAM															
MAN 2	Construction site and surroundings	☑	☑	☑	☐	☑	☑	☐	☐	☑	☑	☐	☐	☐	☐
MAN 3	Construction site impact	☑	☑	☑	☐	☐	☑	☑	☐	☐	☐	☐	☐	☐	☐
MAN 6	Consultation	☐	☐	☐	☐	☐	☐	☐	☐	☐	☑	☐	☐	☐	☑
MAN 8	Security	☐	☐	☐	☐	☐	☐	☐	☐	☐	☑	☐	☐	☐	☐
MAN 9	The development as a learning source	☐	☐	☐	☐	☐	☐	☐	☐	☐	☑	☐	☐	☐	☐
MAN 11	Ease of maintenance	☐	☐	☐	☐	☐	☐	☐	☐	☐	☑	☐	☑	☐	☐
MAN 12	Life cycle costing	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☑	☐	☐
HEA 5	Internal and external lightning levels	☐	☐	☐	☐	☐	☐	☐	☑	☐	☐	☐	☐	☐	☐
HEA 6	Lightning zone and controls	☐	☐	☐	☐	☐	☐	☐	☑	☐	☐	☐	☐	☐	☐
HEA 15	Accessibility	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☑	☐

	Included criteria	Air quality	Water quality	Soil quality	Water consumption	Noise	Sourcing / Waste	Energy	Light	Ecosystem and habitat	Labor safety	Cultural	Future res	Traffic	Stakehold
ENE 1	Reduction of CO2 emission	☑	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
ENE 2a/b	Sub- metering of energy uses - (non) residential	☐	☐	☐	☐	☐	☐	☑	☐	☐	☐	☐	☐	☐	☐
ENE 4	Energy-efficient external lightning	☐	☐	☐	☐	☐	☐	☑	☑	☐	☐	☐	☐	☐	☐
ENE 5	Use of renewable energy	☐	☐	☐	☐	☐	☐	☑	☐	☐	☐	☐	☐	☐	☐
TRA 1a/b/c	Provision of public transport - all	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☑	☐
TRA 3a/b	Alternative modes of transport - (non) residential	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☑	☐
TRA 5	Travel plan and parking policy	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☑	☐
TRA 7	Travel information point	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☑	☐
TRA 8	Deliveries and maneuvering	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☑	☐
WAT 1a/b	Water consumption -(non) residential	☐	☐	☐	☑	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
WAT 2	Water meter	☐	☐	☐	☑	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
WAT 3	Major leak detection	☐	☐	☐	☑	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
MAT 1	Materials specifications	☐	☐	☐	☐	☐	☑	☐	☐	☐	☐	☐	☐	☐	☐
MAT 5	Responsible sourcing of materials	☑	☑	☑	☑	☐	☑	☐	☐	☐	☑	☐	☐	☐	☐
MAT 7	Designing for robustness	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☑	☐	☐
MAT 8	Building flexibility	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☑	☐	☐
WST 1	Waste management on the construction site	☐	☐	☐	☐	☐	☑	☐	☐	☐	☐	☐	☐	☐	☐
WST 2	Recycled aggregates	☐	☐	☐	☐	☐	☑	☐	☐	☐	☐	☐	☐	☐	☐
WST 3a/b	Recyclable waste storage - (non) residential	☐	☐	☐	☐	☐	☑	☐	☐	☐	☐	☐	☐	☐	☐
LE 2	Contaminated land	☐	☐	☑	☐	☐	☑	☐	☐	☐	☑	☐	☐	☐	☐
LE 3	Existing wildlife at the construction site	☐	☐	☐	☐	☐	☐	☐	☐	☑	☐	☐	☐	☐	☐
LE 4	Plants and animals as co-users of the plan area	☐	☐	☐	☐	☐	☐	☐	☐	☑	☐	☐	☐	☐	☐
LE 6	Long - term sustainable co-use by plants and animals	☐	☐	☐	☐	☐	☐	☐	☐	☑	☐	☐	☐	☐	☐
LE 9	Efficient land use	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☑	☐	☐
POL 4	NOx emissions from heating sources	☑	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
POL 6	Surface water run -off	☐	☐	☐	☑	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
POL 7	Reduction of night time light pollution	☐	☐	☐	☐	☐	☐	☐	☑	☐	☐	☐	☐	☐	☐
POL 8	Noise attenuation	☐	☐	☐	☐	☑	☐	☐	☐	☐	☐	☐	☐	☐	☐
Ceequal															
1.1	Project / contract strategy: Evidence of client and designers have undertaken principles of sustainability	☑	☑	☑	☑	☑	☑	☑	☑	☑	☑	☐	☐	☐	☐
2.1	Project / Contract management: Environmental management practices	☑	☑	☑	☐	☐	☐	☐	☐	☑	☐	☐	☐	☐	☐
2.2	Project / Contract management: Social issues that arise from developing, designing and constructing the project	☐	☐	☐	☐	☐	☐	☐	☐	☐	☑	☐	☐	☐	☐
2.3	Project / Contract management: Training	☐	☐	☐	☐	☐	☐	☐	☐	☐	☑	☐	☐	☐	☐
3.1	People and communities: Minimizing operation- and construction-related nuisances	☑	☑	☐	☐	☑	☐	☐	☑	☑	☐	☐	☐	☑	☐
3.2	People and communities: Legal requirements	☐	☐	☐	☐	☐	☐	☐	☐	☐	☑	☐	☐	☐	☐
3.3	People and communities: Community consultation	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☑
3.4	People and communities: Community relations programs and their effectiveness	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☑
3.5	People and communities: Engagement with relevant local groups	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☑
3.6	People and communities: Human environment, aesthetics and employment	☑	☐	☐	☐	☐	☐	☐	☐	☐	☑	☑	☐	☐	☐
4.1	Land use and landscape: Design for optimum land-take	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☑	☐	☐
4.2	Land use and landscape: Legal requirements	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☑	☐	☐	☐
4.3	Land use and landscape: Flood risks	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☑	☐	☐
4.4	Land use and landscape: Previous use of the site	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☑	☐	☐	☐
4.5	Land use and landscape: Land contamination	☐	☐	☑	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐

	Included criteria	Air quality	Water quality	Soil quality	Water consumption	Noise	Sourcing / Waste	Energy	Light	Ecosystem and habitat	Labor safety	Cultural	Future res	Traffic	Stakehold
4.6	Land use and landscape: Remediation measures	☐	☐	☐	☐	☐	☐	☐	☐	☑	☐	☐	☐	☐	☐
4.7	Land use and landscape: Conventional land use	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☑	☐	☐	☐
4.11	Land use and landscape: Landscape local character	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☑	☐	☐	☐
4.12	Land use and landscape: Loss and compensation or mitigation features	☐	☐	☐	☐	☐	☐	☐	☐	☑	☐	☐	☐	☐	☐
4.13	management	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☑	☐	☐	☐
4.14	Land use and landscape: Completion and aftercare	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☑	☐	☐	☐
5.1	Historic Environment: Conservation and enhancement measure	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☑	☐	☐	☐
5.2	Historic Environment: Information and public access	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☑	☐	☐	☐
6.1	Ecology and Biodiversity: Habitat creation measures	☐	☐	☐	☐	☐	☐	☐	☐	☑	☐	☐	☐	☐	☐
6.2	Ecology and Biodiversity: Habitat monitoring	☐	☐	☐	☐	☐	☐	☐	☐	☑	☐	☐	☐	☐	☐
6.3	Ecology and Biodiversity: Habitat maintenance	☐	☐	☐	☐	☐	☐	☐	☐	☑	☐	☐	☐	☐	☐
6.4	Ecology and Biodiversity: Protected species	☐	☐	☐	☐	☐	☐	☐	☐	☑	☐	☐	☐	☐	☐
6.5	Ecology and Biodiversity: Surveys conservations & enhancement	☐	☐	☐	☐	☐	☐	☐	☐	☑	☐	☐	☐	☐	☐
6.6	Ecology and Biodiversity: Ecological value	☐	☐	☐	☐	☐	☐	☐	☐	☑	☐	☐	☐	☐	☐
7.1	Water environment : Water environment protection	☐	☑	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
7.2	Water environment : Legal requirements	☐	☑	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
7.3	Water environment: Enhancement of water environment	☐	☑	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
8.1	Physical resources use and management: LCA	☐	☐	☐	☐	☐	☑	☐	☐	☐	☐	☐	☑	☐	☐
8.2	Physical resources use and management: Energy and carbon emissions in use	☑	☐	☐	☐	☐	☐	☑	☐	☐	☐	☐	☐	☐	☐
8.3	Physical resources use and management: Energy and carbon performance on site	☑	☐	☐	☐	☐	☐	☑	☐	☐	☐	☐	☐	☐	☐
8.4	Physical resources use and management: Minimizing use and impacts of hazardous materials	☐	☐	☑	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
8.5	Physical resources use and management: Minimizing material use and waste	☐	☐	☐	☐	☐	☑	☐	☐	☐	☐	☐	☐	☐	☐
8.6	Physical resources use and management: Responsible sourcing of materials incl. timber	☑	☑	☑	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
8.7	Physical resources use and management: Using reused /recycled materials	☐	☐	☐	☐	☐	☑	☐	☐	☐	☐	☐	☐	☐	☐
8.8	Physical resources use and management: Durability and maintenance	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☑	☐	☐
8.9	Physical resources use and management: Future deconstruction or disassembly	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☑	☐	☐
8.10	Physical resources use and management: Design for waste minimization	☐	☐	☐	☐	☐	☑	☐	☐	☐	☐	☐	☐	☐	☐
8.11	Physical resources use and management: Legal requirements	☐	☐	☐	☐	☐	☑	☐	☐	☐	☐	☐	☐	☐	☐
8.12	Physical resources use and management: Waste from site preparation	☐	☐	☐	☐	☐	☑	☐	☐	☐	☐	☐	☐	☐	☐
8.13	Physical resources use and management: Minimizing water consumption and embodied water	☐	☐	☐	☑	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
8.14	Physical resources use and management: Policies and targets for resource efficiency	☐	☐	☐	☐	☐	☑	☐	☐	☐	☐	☐	☐	☐	☐
8.15	Physical resources use and management: On-site waste management	☐	☐	☐	☐	☐	☑	☐	☐	☐	☐	☐	☐	☐	☐
9.1	Transport: Minimizing traffic impacts of a project	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☑	☐
9.2	Transport: Construction transport	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☑	☐
9.3	Transport: Minimizing workforce travel	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☑	☐

	Included criteria	Air quality	Water quality	Soil quality	Water consumption	Noise	Sourcing / Waste	Energy	Light	Ecosystem and habitat	Labor safety	Cultural	Future res	Traffic	Stakehold
9.4	Transport: Access for pedestrian and cyclist	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☑	☐
9.5	Transport: Need for add. transport infrastructure arising for the project	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☑	☐
9.6	Transport: Resilience of the network	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☑	☐
9.7	Transport: Performance for non-motorized users	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☑	☐
Ambitieweb															
1.1	Trustful and robustness	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☑	☐
1.2	Efficient infrastructure use	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☑	☐
1.3	Accessible functions	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☑	☐
1.4	Sustainable mobility	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☑	☐
2.1	Value of experience	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☑	☐	☐	☐
2.2	Value of future	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☑	☐	☐
3.1	Connection to regional development	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☑	☐
3.2	Urbanization and efficient area use	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☑	☐	☐
3.3	Multiple area use	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☑	☐	☐
4.1	Habitat diversity and quality	☐	☐	☐	☐	☐	☐	☐	☐	☑	☐	☐	☐	☐	☐
4.2	Rest of flora and fauna	☐	☐	☐	☐	☐	☐	☐	☐	☑	☐	☐	☐	☐	☐
5.1	Energy reduction	☐	☐	☐	☐	☐	☐	☑	☐	☐	☐	☐	☐	☐	☐
5.2	Renewable energy	☐	☐	☐	☐	☐	☐	☑	☐	☐	☐	☐	☐	☐	☐
5.3	Energy saving	☐	☐	☐	☐	☐	☐	☑	☐	☐	☐	☐	☐	☐	☐
6.1	Healthy environment	☑	☑	☑	☐	☑	☐	☐	☑	☐	☑	☐	☐	☐	☐
6.2	Save environment	☐	☐	☐	☐	☐	☐	☐	☐	☐	☑	☐	☐	☐	☐
6.3	Physical training	☐	☐	☐	☐	☐	☐	☐	☐	☐	☑	☐	☐	☐	☐
7.1	Clusters	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☑	☐	☐
7.2	Knowledge infrastructure	☐	☐	☐	☐	☐	☐	☐	☐	☐	☑	☐	☐	☐	☐
8.1	Life cycle costs	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☑	☐	☐
8.2	Future proof investments	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☑	☐	☐
9.1	Material reduction	☐	☐	☐	☐	☐	☑	☐	☐	☐	☐	☐	☐	☐	☐
9.2	Preservation of value	☐	☐	☐	☐	☐	☑	☐	☐	☐	☐	☐	☐	☐	☐
9.3	Adaptable, maintainable and reusable	☐	☐	☐	☐	☐	☑	☐	☐	☐	☐	☐	☐	☐	☐
9.4	Sustainable materials	☑	☑	☑	☑	☐	☑	☐	☐	☐	☐	☐	☐	☐	☐
10.1	Community support and local expertise	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☑
10.2	Social inclusivity	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☑
11.1	Soil quality	☐	☐	☑	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
11.2	Soil system	☐	☐	☑	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
11.3	Archaeological values	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☑	☐	☐	☐
12.1	Water safety	☐	☑	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
12.2	Reduction of water hindrance	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☑	☐	☐
12.3	Water quality	☐	☑	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
12.4	Extreme weather	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☑	☐	☐

Figure A.8: Operational objective test to sustainability definition

B

Sustainable assessment of quay wall development

In this Appendix, the fourteen aspects of sustainability are described and assessed using a method for assessment and management of sustainability (Laboyrie et al., 2018). This is the Frame of Reference.This method is a continuous process between various stakeholders. In this report, an initial assessment is made using literature sources. If an element of the assessment method can not be determined, this means that the author didn't found a reliable source to describe the element or to verify the statement. At the end of each aspect, a conclusion is made that indicates which elements of the aspect are defined and which ones are not. This is indicated with different colors. The color green signifies that the concerned element is defined by a reliable source. The yellow color indicates that the element is defined, although the definition raised question by the author. The reasoning why will be described as well. The color red signifies that the element is not defined by a reliable source.

B.1. Air pollutants

Strategic objective	Source
To achieve levels of air quality that do not result in unacceptable impacts on, and risks to, human health and the environment.	(European Environment Agency, 2017)

According to the European Environment Agency's webpage (European Environment Agency, 2017), a quality level that do not result in unacceptable impacts on, and risks to, human health and the environment, is wanted. This is the strategic objective related to air pollution. Air pollutants can be divided in the following gases: greenhouse gases (GHG's), toxic gases that create health problems to the local community, and remaining non-toxic gases that create health problems. Firstly, greenhouse gases are all the gases recognized by the Kyoto Protocol, that contribute to the global warming. These gases will be further explained in the operational objective B.1.1

Secondly, hazardous emissions are regulated in Europe by maximum allowed concentrations. The following gases are defined: sulphur dioxide (SO_2), nitrogen oxides (NO_x), particle matters (PM10 and PM2,5), carbon oxide (CO), lead, benzene, ozone, arsenic, cadmium, nickel and benzopyrene. Scientific evidence shows that some of these components (i.e. arsenic, cadmium, nickel) are toxic and have no identifiable threshold below which these components do not create health risks (E.P. & C.o.E, 2015). Minimizing the emission of those components should be the goal. In this objective, the aim is to quantify the following main air pollutants in construction and navigation projects: particle matters (PM10), sulphur dioxide (SO_2) and nitrogen oxides (NO_x) (Font et al., 2014), (Lonati et al., 2010)) and (Port of Rotterdam, 2014). The other gases are not considered further due their minor emission in construction and navigation. At last, non-toxic gases that create odor hindrance will be considered.

B.1.1. Operational objective 1.1: Greenhouse gases

Operational objective	Source
The emission of greenhouse gases should be reduced to have a climate neutral society in 2050.	(European Commission, 2018a)

This operational objective can be found in an E.U. report from 2018 (European Commission, 2018a). Greenhouse gases refer to seven gases that have direct effects on climate change: carbon dioxide (CO_2), methane (CH4), nitrous oxide (N2O), chlorofluorocarbons (CFCs), hydrofluorocarbons (HFCs), perfluorocarbons (PFCs), sulphur hexafluoride (SF6) and nitrogen trifluoride (NF3). Six gases of those gases (CO_2, CH4, N2O, HFCs, CFCs, and SF6) comprise the major GHG that are recognized by the GHG Protocol (WRI, 2013). Nitrogen trifluoride (NF3) is mostly used in electronics industry, hence it is not emitted during the life time of a quay wall and it will be neglected further.

Quantitative state concept:

Greenhouse gases are expressed in global warming potential (GWP). These potentials indicate, on a ton-by-ton basis, how much a gas will contribute to global warming, relatively to how much warming would be caused by the same mass of CO_2. GWP is equal to one carbon dioxide equivalent (CO_2-eq) which is measured in tons. Note that GWPs can change over time due to new research, hence updating the numbers frequently is necessary. The GHG, their related GWP and their emission sources related to navigation infrastructure construction and operation, are depicted in Figure B.1.

GHGs	100-Year Global Warming Potential (GWP) – [IPCC, 2014]	Example Navigation Infrastructure Sources
Carbon dioxide (CO_2)	1	Fossil fuel combustion in boilers and generators, from purchased electricity and from on and off-road mobile sources.
Methane (CH_4)	28	By-products of fossil fuel combustion; created ecosystem anaerobic by-product.
Nitrous oxide (N_2O)	265	By-products of fossil fuel combustion.
Hydrofluorocarbons (HFCs)	4-12,400	Refrigeration leaks from HVAC systems and automotive air conditioning systems.
Chlorinated fluorocarbons (CFCs)	79-13,900	Unlikely to be present; manufacture of CFCs has been phased out under the Montreal Protocol – historically was widely used as refrigerants, propellants and solvents.
Sulphur hexafluoride (SF_6)	23,500	Unlikely to be present; primary use is in electrical equipment and specific industrial processes.

Figure B.1: The six most likely emitted greenhouse gasses during construction and navigation projects and their related GWP and emission sources. Source: (PIANC, 2019)

The production and usage of materials and fuels are the main cause of the emission of GHG. LCA methods are a common way to calculate GHG emissions (NEN, 2006). In these LCAs, calculation of emitted CO_2-eq are done which results in CO_2-eq key variables for machinery, engines and chemical processes. These calculations are performed by officially recognized organisations. During the life cycle of a quay wall, the emission of GHG is mostly present in the production, construction and end-of-life phase. The maintenance of a quay wall is minimal. The usage of the quay wall (by a third party) is out of scope. An example sketch of GHG emission in time for a quay wall (present, in 2030 and in 2050) is shown in Figure B.2.

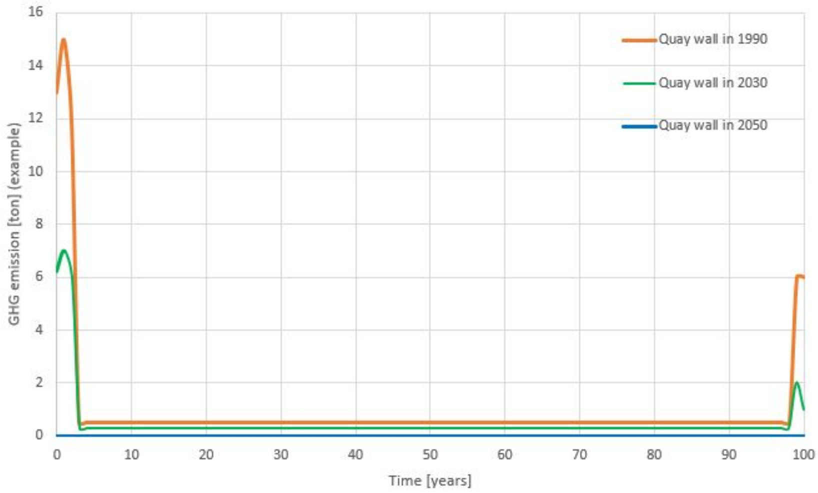


Figure B.2: An example sketch of the emission of GHG in the 100 year life cycle of a quay wall (in the present, in 2030 and in 2050). The emission of GHG is mostly found in the production, construction and end-of-life phase.

The GHG emission of materials, machinery and vehicles can be quantified using standard key values. However, this quantification tool that is based on the life cycle method is not identified yet.

Benchmarking procedure:

At the moment, the GHG emission in quay wall projects is not known. Hence the current state is not defined. The desired state is in line with the Paris Climate Agreement. According to the report of European Commission (2018a), the European Union should be carbon neutral in 2050. In the Netherlands, a reduction of 49 % in 2030 and of 95 % in 2050 compared to 1990 is desired (van Vuuren, Boot, Ros, Hof, & den Elzen, 2017). For infrastructure (including quay walls projects), the ambition is to be carbon neutral in 2030 (Rijkswaterstaat (Rijkswaterstaat, 2018)) or in 2050 (PoR (Port of Rotterdam Insight, 2017) and Prorail (Prorail, 2018)). Intermediate targets are not known. These in-between targets should be set up to indicate if the ultimate target is still possible. If this would be done in line with the Dutch government ambition, this would mean that GHG should be reduced with 49 % in 2030 compared to 1990. This causes the following problem. There is no information on the emission of GHG in quay wall development in 1990. This means the reference state can not be determined.

Additional information: The ultimate target of 2050 is approximately thirty years from now. The authorities has two option at this point. First one is to do nothing at the moment and let the market do 'its' work. As an example, a port authority could look in the year 2048 to their assets and use the techniques that are available at that moment to achieve their goal. However the authority has an important influence in the process, which can not be neglected. In the interviews performed with van contractors (see Appendix C.2), they both expressed their feelings about how the port authority should steer sustainability to persuade the market. As an authority, it can express particular themes as important and give it a financial stimulant (i.e. M.V.I process). The contractors are not going to change on environmental policy if the client does not ask for it (see Appendix C.2). So from those statements and from the operational objective, action is needed.

Intervention procedure:

Their are possible intervention procedures that could reduce the emission, although there are no general solutions yet. Design changes, material changes, using green energy, materials from local producers (reducing the transport distances), materials with a lower GHG footprint, less material use and circularity, etc, could reduce the emission of GHG. But their impact is not quantified yet, hence further research is advised. Another solution could be to stop new projects and maintenance work when intermediate emission limits are achieved. Although this would lead to waiting lists and an undesirable economical effects.

Evaluation

The LCA method considers all the emitted gases during a life time cycle and extrapolates to one year. Comparing the emission of the different years gives a reduction percentage which indicates if the desired goals are achieved. Figure B.3 shows the extrapolation of Figure B.2 per year and the possible reductions expressed in percentages.

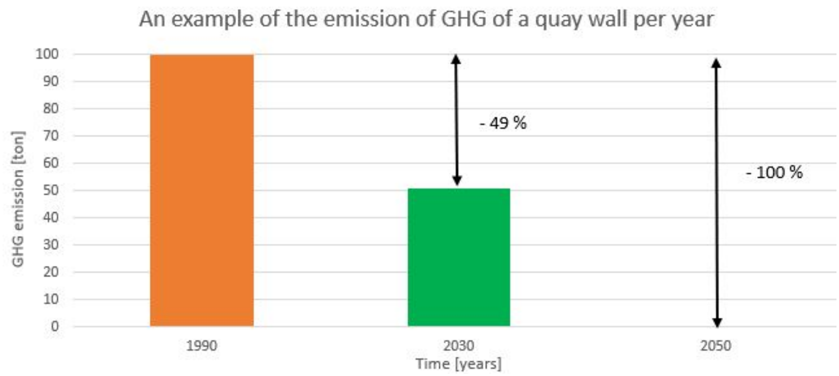


Figure B.3: An example of the emission of GHG in the 100 year life cycle of a quay wall. The emission of GHG is extrapolated to one year.

Applying this method causes a situation in which a part of the emission is already accounted as emitted. This is not the case in reality, in which the GHG of the maintenance and end-of-life phase are not emitted. Long life cycles of 100 years as can be seen by quay walls, have a large uncertainty if the emission will be eventually be emitted or not. The LCA key values give an indication of the expected emission, as it was determined in a lab. It is not calculated during the actual construction, hence it doesn't give the exact value, but an expected averaged value. Secondly, the emission is project specific which means that quantity, type and size of projects vary. This makes it difficult to control the achieved reduction of emission in general. For example, in year X there are 10 projects and the next year (year Y) there are 4 projects. The cumulative GHG emission of year X is higher than year Y, so a reduction is achieved. The following year (year Z) has 12 projects, hence the emission increases. The 'achieved' reduction is lost. Looking per project could give more insight in the achieved reduction but due to the variety of the projects, it is difficult to compare them. A solution how to account the emission is not found yet. Further research should be done.

Results

Figure B.4 shows the elements of the Frame of Reference and their related colors. The strategic, operational objective and the desired state are determined by a reliable source and indicated in green. The quantitative state concept can be determined, however an objective quantification tool that is based on the LCA method, is not identified yet. That is why it is indicated in yellow. The intervention measures are proposed as well, although the impact is not quantified. This is indicated in yellow as well. The current state is not standard calculated for projects and not done for a quay wall specifically. The evaluation procedure are not identified either. These are both indicated in red.

Sustainability aspect		Strategic objective	Operational objective	Quantitative state concept	Benchmark procedure		Intervention	Evaluation
					Current state	Desired state		
Air pollutants	1.1 Greenhouse gases							

Figure B.4: Results of operational objective 1.1: Greenhouse gases, in aspect of sustainability: Air pollutants

Due to these unknowns, it is not possible how one party will achieve the desired situation of carbon neutrality in 2050. This topic needs further research.

B.1.2. Operational objective 1.2: Sulphur dioxide

Operational objective	Source
The concentration of sulphur dioxide (SO_2) should be below 20 μg/m^3 for 24-hour mean, 350 μg/m^3 for hour mean and 500 μg/m^3 for 10-minute mean . In general, the emission should be reduced with 28 % in 2020 compared to 2005.	(World Health Organization, 2006), (Ministerie van Binnenlandse Zaken en Koninkrijksrelaties, 2019) and (E.P. & C.o.E., 2016)

Sulphur dioxide is a gas that is released during the combustion of fossil fuel. Higher concentrations of SO_2 could cause respiratory complaints to people with asthma or chronicle lung diseases. In addition, sulphur dioxide causes acidification and eutrophication.

Quantitative state concept:
Sulphur dioxide is a combustion gas that is emitted through engines. Specific key values of SO_2 can be used to quantify the expected emission. However, if the total emission of SO_2 should be reduced, the LCA method is required. This is not possible with the specific key values. Another quantification tool is not identified yet.

Benchmarking procedure:
The current situation can be determined using the key values. This is the same principle as in operational objective B.1.1. At the moment, the emission of sulphur dioxide is determined for specific projects, however the general emission of a quay wall is not.

The desired situations can be separated into two parts. One is the desired goal to stay below the maximum concentration that is harmful for the environment. This is short term and can be seen per project. It is calculated beforehand. The World Health Organization set the guideline at 20 μg/m^3 for 24-hour mean and 500 μg/m^3 for 10-minute mean (World Health Organization, 2006). The Port of Rotterdam applies 'Wet milieubeheer'. In chapter 5, title 5.2 'Luchtkwaliteiteisen' the quality criteria of air emission in the Netherlands is addressed. This law of 2017 is known as 'Wet luchtkwaliteit' (Wlk) (Ministerie van Binnenlandse Zaken en Koninkrijksrelaties, 2019). For sulphur dioxide regulations, the maximum concentrations can be found in Table B.1. When applying the most strict guideline, this would mean that the concentration of SO_2 should be below 20 μg/m^3 for 24-hour mean, 125 μg/m^3 for hour mean and 500 μg/m^3 for 10-minute mean.

Table B.1: Dutch regulation on sulphur dioxide. Source:(Ministerie van Binnenlandse Zaken en Koninkrijksrelaties, 2019)

Time	**Concentration [$\frac{\mu g}{m^3}$]**
Day average concentration, max 3 times a year exceeded	125
Hour average concentration, max 24 times a year exceeded	350

The second desired goal is the emission reduction on the long term. Under the revised protocol, the EU is set to reduce its SO_2 emission for 2020 with 28 % compared to 2005 (E.P. & C.o.E., 2016). However the reference state of 2005 is not known.

Intervention procedure:
Possible intervention measures are the electrification of machinery, usage of different fuels and usage of after-treatment installations like scrubbers. For the maximum allowed concentration levels, an additional possible intervention could be to optimize the construction schedule. However, the impact of these measures are not quantified.

Evaluation
The concentration of SO_2 should be below 20 μg/m^3 for 24-hour mean, 125 μg/m^3 for hour mean and 500 μg/m^3 for 10-minute mean. This is calculated beforehand to not cross these limits. In practice, the actual levels are not measured. In addition, a solution how to account the emission is not found yet. This is the same reason as described in operational objective B.1.1.

Results

Figure B.5 shows the elements of the Frame of Reference and their related colors. The strategic and operational objective are identified by a reliable source and indicated in green. The quantitative state concept, current state, desired state and intervention procedure are indicated in yellow, due to a missing quantification tool based on the LCA method, a missing current quantified quay wall, a missing 2005 reference base and a missing quantification of the impact of the solutions. The evaluation procedure is not identified yet and indicated in red.

Sustainability aspect		Strategic objective	Operational objective	Quantitative state concept	Benchmark procedure		Intervention	Evaluation
					Current state	Desired state		
Air pollutants	1.2 Sulphur dioxide							

Figure B.5: Results of operational objective 1.2: Sulphur dioxide, in aspect of sustainability: Air pollutants

B.1.3. Operational objective 1.3: Nitrogen oxides

Operational objective	Source
The concentration level of nitrogen oxides (NO_x) should be below 40 µg/m^3 for annual mean and 200 µg/m^3 for hour mean. In general, the emission should be reduced with 42 % in 2020 compared to 2010.	(World Health Organization, 2006), (Ministerie van Binnenlandse Zaken en Koninkrijksrelaties, 2019) and (E.P. & C.o.E., 2016)

Nitrogen oxides are combustion gases. Exposure to nitrogen oxides will cause a reduced pulmonary function. It causes an increase in breathing problems and asthma attacks, and sensitivity to infections may increase. In addition, nitrogen oxides cause acidification and eutrophication.

Quantitative state concept:

Specific key values of NO_x can be used to quantify the expected emission. However, if the total emission of NO_x should be reduced, the LCA method is required. This is not possible with the specific key values. Another quantification tool is not identified yet.

Benchmarking procedure:

The current situation can be determined by using the key values. This is the same principle as in operational objective B.1.1. At the moment, the emission of nitrogen dioxide is determined for specific projects, however the general emission of a quay wall is not.

The desired situations can be separated into two parts. One is the desired goal to stay below the maximum concentration that is harmful for the environment. This is short term and can be seen per project. It can be calculated beforehand. The World Health Organization set the guideline at 40 µg/m^3 for annual mean and a 200 µg/m^3 for 1-hour mean (World Health Organization, 2006). The port of Rotterdam applies 'Wet milieubeheer'. In chapter 5, title 5.2 'Luchtkwaliteiteisen' the quality criteria of air emission in the Netherlands is addressed. This law (2017) is known as 'Wet luchtkwaliteit' (Wlk) (Ministerie van Binnenlandse Zaken en Koninkrijksrelaties, 2019). For nitrogen dioxide regulations, the maximum concentrations can be found in Table B.2. When applying the most strict guideline, this would mean that the concentration of NO_x should be below 40 µg/m^3 for annual mean and a 200 µg/m^3 for 1-hour mean.

Table B.2: Dutch regulation on nitrogen oxides. Source: (Ministerie van Binnenlandse Zaken en Koninkrijksrelaties, 2019)

Time	**Concentration [$\frac{\mu g}{m^3}$]**
Yearly average concentration	40
Hour average concentration, max 18 times a year exceeded	200

The second desired goal is the emission on the long term. Under the revised protocol, the EU is set to reduce its emissions for 2020 as follows: nitrogen oxides reduction 42% compared to 2010 (E.P. & C.o.E., 2016). However the reference state of 2010 is not known for quay wall development.

Intervention procedure:

Possible intervention measures are the electrification of machinery, usage of different fuels and usage of after-treatment installations like scrubbers. For the maximum allowed concentration levels, an additional possible intervention could be to optimize the construction schedule. However, the impact of these measures are not quantified.

Evaluation

The concentration of NO_x should be below 40 μg/m^3 for annual mean and a 200 μg/m^3 for 1-hour mean. This is calculated beforehand to not exceed these limits. In practice, the actual levels are not measured. In addition, a solution how to account the emission is not found yet. This is the same reason as described in the operational objective 1.1.

Results

Figure B.6 shows the elements of the Frame of Reference and their related colors. The strategic and operational objective are identified by a reliable source and indicated in green. The quantitative state concept, current state, desired state and intervention procedure are indicated in yellow, due to a missing quantification tool based on the LCA method, a missing current quantified quay wall, a missing 2010 reference base and a missing quantification of the impact of the solutions. The evaluation procedure are not identified yet.

Sustainability aspect		Strategic objective	Operational objective	Quantitative state concept	Benchmark procedure		Intervention	Evaluation
					Current state	Desired state		
Air pollutants	1.3 Nitrogen oxides							

Figure B.6: Results of operational objective 1.3: Nitrogen oxides, in aspect of sustainability: Air pollutants

B.1.4. Operational objective 1.4: Particle matter

Operational objective	Source
The concentration of particle matters PM_{10} should be below 20 μg/m^3 for annual mean, 50 μg/m^3 for day mean.	(World Health Organization, 2006) and (Ministerie van Binnenlandse Zaken en Koninkrijksrelaties, 2019)

The exposure of particulate matter PM_{10} in urban areas leads to adverse health effects for the human population. The range of health effects is broad, but are predominantly to the respiratory and cardiovascular systems.

Quantitative state concept:

There is a direct relation with PM_{10} found by the RIVM in which there is a constant distribution between PM_{10} and $PM_{2.5}$. When the maximum concentration of PM_{10} is respected, the maximum concentration of $PM_{2.5}$ will not be exceeded (Matthijssen, Jimmink, de Leeuw, & Smeets, 2009). That is why it is chosen by the author to only consider PM_{10} further. Specific key values of PM_{10} can be used to quantify the expected emission. This method does not have to be based on the LCA method as there is no goal on total reduction of emission.

Benchmarking procedure:

The current situation can be determined by using the key values. This is the same principle as in operational objective 1.2.

The desired goal is to not exceed the maximum concentration that is harmful for the environment. This is short term and it can be seen per project. As reference, the World Health Organization set the guideline for $PM_{2.5}$: 10 μg/m^3 annual mean and 25 μg/m^3 24-hour mean, for PM_{10}: 20 μg/m^3 annual mean and 50 μg/m^3 for 24-hour mean. According to the Wlk, particle matters can be divided in $PM_{2.5}$ and PM_{10}. The regulations for PM_{10} can be found in Table B.3. For $PM_{2.5}$ a year average of 25 $\frac{\mu g}{m^3}$ can be found.

Table B.3: Dutch regulation on particle matters PM_{10}. Source: (Ministerie van Binnenlandse Zaken en Koninkrijksrelaties, 2019)

Time	**Concentration** $[\frac{\mu g}{m^3}]$
Yearly average concentration	40
Day average concentration, max 35 times a year exceeded	50

These following concentrations of PM_{10} should be used as a maximum concentration: 20 μg/m^3 annual mean and 50 μg/m^3 24-hour mean.

Intervention procedure:

Possible intervention measures are the electrification of machinery, usage of different fuels and usage of after-treatment installations like scrubbers. For the maximum allowed concentration levels, an additional possible intervention could be to optimize the construction schedule. However, the impact of these measures are not quantified. More research is advised.

Evaluation

The emission of particle matters is calculated beforehand to predict the total emission. In practice, the actual levels during construction are not measured. The evaluation is project specific as there are no general targets found by the author.

Results

Figure B.7 shows the elements of the Frame of Reference and their related colors. The strategic and operational objective, the quantitative state concept, the desired state and the evaluation procedure is identified by a reliable source and indicated in green. The desired state is indicated in yellow, because it is only known for specific projects and not known for a general quay wall. The impact of the intervention measures is not identified yet and indicated in yellow as well.

Sustainability aspect		Strategic objective	Operational objective	Quantitative state concept	Benchmark procedure		Intervention	Evaluation
					Current state	Desired state		
Air pollutants	1.4 Particle matter							

Figure B.7: Results of operational objective 1.4: Particle matter, in aspect of sustainability: Air pollutants

B.1.5. Operational objective 1.5: Odor

Operational objective	Source
In general, outside the terrain, odor may not be detectable. Concentration levels should be below 0.5 $\frac{ouE}{m^3}$ **with a 99,99 percentile at the border of the terrain.**	(DCMR Milieudienst Rijnmond, 2013b)

The last operational objective aims to tackle the problem of odor annoyance. This is a non-toxic air pollutant that affects the quality of life and therefore the social well-being of the health (World Health Organization, 2018).

Quantitative state concept:

Odor nuisance due to industry are normally expressed in European Odor Units (NEN, 2003). It is applicable for the measurements of concentrations of pure substances. The odour concentration is measured by determining the dilution factor required to reach the detection threshold. The unit of measurement is the European odour unit per cubic meter: ouE/m^3. The range of measurement is typically from 101 ouE/m^3 to 107 ouE/m^3 (including pre-dilution). This measurement is combined with regulated percentiles. A common percentile is 98 % which says that 98 % of the time, the odor regulations cannot be exceeded.

Benchmarking procedure:
The current state can be predicted by calculation. Actual numbers are normally not measured. If hindrance occurs, it can be measured. There is not an current state for quay walls identified.

In article 2.7a of the 'Activiteitenbesluit' and the information document 'Handleiding Geur' describes the determination of an acceptable odor level of industries and to prevent new odor nuisance. The 'Activiteitenbesluit' describes a couple of activities which are limited by an acceptable nuisance level. In addition, local authorities of the Netherlands developed their own regulations. In general, there is odor nuisance if the yearly emission is 0.5 $\frac{ouE}{m^3}$ with a 98 percentile near housing is exceeded. This means that on location the concentration of 0.5 $\frac{ouE}{m^3}$ 98% of the year is not exceeded. If peak emission occur, the 98% limit will be too low and a percentage of 99,99 % is more likely to be used.

In the area of Rijnmond, additional regulations are written due to the combinations of odors. The regulations says that outside the terrain border no odor must be detectable from the terminal. However, different levels of protection are considered in the 'Geuraanpak' due to different surroundings (DCMR Milieudienst Rijnmond, 2013b):

1. Level 1: Outside the terrain, odor may not be detectable. The guideline is in order of 0.5 $\frac{ouE}{m^3}$ with a 99,99 percentile at the border of the terrain.

2. Level 2: At the vulnerable location, odor may not be detectable. The guideline is in order of 0.5 $\frac{ouE}{m^3}$ with a 99,99 percentile at the border of the terrain.

3. Level 3: At the vulnerable location, odor may not be detectable. The guideline is in order of 0.5 $\frac{ouE}{m^3}$ with a 98.00 percentile at the border of the terrain.

Intervention procedure:
A intervention measure could be to stop using internal combustion engines which emit odor enhancing gases.

Evaluation
Evaluation can be done by measuring at the construction site when the odor hindrance occur.

Results
Figure B.8 shows the elements of the Frame of Reference and their related colors. Almost all the elements can be determined by a reliable source. They are indicated in green. The current state is indicated in yellow as it is not identified for quay walls specifically.

Sustainability aspect		Strategic objective	Operational objective	Quantitative state concept	Benchmark procedure		Intervention	Evaluation
					Current state	Desired state		
Air pollutants	1.5 Odor							

Figure B.8: Results of operational objective 1.5: Odor, in aspect of sustainability: Air pollutants

B.2. Water pollutants

Strategic objective	Source
To reduce emission of water pollutants below a certain level that will harm the environment.	(European Environment Agency, 2018), (United Nations, 2018)

The following water pollutants are considered: nitrogen, phosphorus, water turbidity, heavy metals and concentration of oil. Nitrogen en phosphorus components in water are essential for plant and animal growth, but overabundance of these components have adverse health and ecological effects. During the life time of a quay wall, these components are emitted through the air and get in contact with water. This causes eutrophication and acidification of water. Assuming that this emission is through the air, these components will be considered as air pollutants and will not be discussed in this aspect.

B.2.1. Operational objective 2.1: Water turbidity

Operational objective	Source
The water turbidity should be below the concentration levels that will harm present receptors.	(European Commission, 2018b)

Water turbidity is defined as the generation of suspended solids which leads to light attenuation and smothering of neighbouring seabeds. It affects receptors as marine fauna and flora, and influences the biodiversity present in the water. High turbidity could block out light that plants needs to develop. The coherent plant decline will have consequences for animals. In addition, higher turbidity due to suspended particles worsens sight of fish and may clog the gills of fish which could cause death.

Quantitative state concept:

The Suspended Sediment Concentration (SSC) [mg/l] in the near- and far-field is used to quantify the dredging-induced turbidity. The first step would be to check whether there are any sensitive receptors affected during the construction. If this is the case, step two would be to assess a worst-case scenario using a 1D Advection Diffusion Equation. The worst case scenario can be determined at the receptors location. When action is needed, step three would be further research using models and tools. This concept is described in the book of Laboyrie et al. (2018) and will not be explained further.

Benchmarking procedure:

The concentration that occurs is not known for quay wall projects specifically. It is for different machinery and barges. The desired state is a maximum value. A general maximum is not found in the literature. The maximum concentration levels depend on the present receptors and their capability levels.

Intervention procedure:

Intervention could be done by changing dredging methodology (type of dredger, production rate, placement method, mitigation measures) or the dependence on hydrodynamic conditions during and after dredging.

Evaluation

The maximum allowable Suspended Sediment Concentration depends on the resistance of the receptors. That's why there is no general fixed value found. The expected state is calculated, but the actual state is not measured during construction.

Results

Figure B.9 shows the elements of the Frame of Reference and their related colors. Almost all the elements can be determined by a reliable source. They are indicated in green. The current state and desired state are indicated in yellow. The current state is not known for quay wall development. The desired state is depending on the different receptors and is project specific. Research into all the possible receptors should be done to considers this element as green.

Sustainability aspect		Strategic objective	Operational objective	Quantitative state concept	Benchmark procedure		Intervention	Evaluation
					Current state	Desired state		
Water pollutants	2.1 Water turbidity							

Figure B.9: Results of operational objective 2.1: Water turbidity, in aspect of sustainability: Water pollutants

B.2.2. Operational objective 2.2: Contaminants

Operational objective	Source
The emission of contaminants in water should be below the concentration level that will harm the environment.	(E.P. & C.o.E, 2008)

Contaminants that may be present in the soil (like heavy metals) can be redistributed through the water when construction work is being executed. It can have a severe influence on water quality and the present receptors nearby.

Quantitative state concept:
To quantify the present pollution in the water body, samples are taken from the water at the source and the contaminants are expressed in grams per liter. The following contaminants are considered : cadmium (Cd), copper (Cu), mercury (Hg), zinc (Zn), chromium (Cr), lead (Pb), nickel (Ni) and oil (OSPAR Commission, 1998).

Benchmarking procedure:
The current state is calculated and measured before construction. Guidelines which provide an indication of the threshold for which feasible effects could occur, should be used. Some countries have their own regulations on this topic, other countries depend on more general guidelines. For this research, Annex II of the amended directives 2008/105/EC of the European commission (E.P. & C.o.E, 2008) which defines the limits of the heavy metals in water, and Directive 76/464/EEC codified as 2006/11/EC which defines the limits of oil concentrations (E.P. & C.o.E., 2006), are consulted. According to E.P. and C.o.E (2008), the following metals are not applicable: copper (Cu), zinc (Zn), chromium (Cr) and nickel (Ni). These are not discussed further.

Directive 76/464/EEC codified as 2006/11/EC recommends an oil concentration < 5 to 10 mg/l depending upon the quantity of the discharge and the receiving environment (E.P. & C.o.E., 2006). In descriptive terms "no visible oil" has been also been frequently used. For refineries in Europe, an annual average of a maximum of 5 mg/l in the effluents was noted in PARCOM Recommendation 89/5 (Yang, 2016).

Summing up the information from the literature, gives the following lists of limit concentrations.

- Cadmium (Cd) depending on hardness of the water < 1,5 µg/l (maximum level)
- Mercury (Hg) < 0.07 µg/l
- Lead (Pb) < 14 µg/l
- Oil < 5 mg/l

Intervention procedure:
Possible interventions measures should avoid the contact between water and the contaminated land. This will be discussed in Paragraph B.3

Evaluation
For the contaminants, maximum concentration levels can be found that would assure no harm to the present receptors. These concentrations should be taken into account for sustainable production and construction of a quay wall. Evaluation can be done when samples are taken before and during the construction to cross check with the desired situation.

Results

Figure B.10 shows the elements of the Frame of Reference and their related colors. All the elements can be determined by a reliable source. They are indicated in green.

Sustainability aspect		Strategic objective	Operational objective	Quantitative state concept	Benchmark procedure		Intervention	Evaluation
					Current state	Desired state		
Water pollutants	2.2 Contaminants							

Figure B.10: Results of operational objective 2.2: Contaminants, in aspect of sustainability: Water pollutants

B.3. Soil pollutants

Strategic objective	Source
To reduce the impact of soil pollutants below a level that will harm the environment.	(E.P. & C.o.E., 2002)

B.3.1. Operational objective 3.1: Contaminants

Operational objective	Source
Concentration of contaminants in the soil that will release in the water, should be below levels that will harm the environment.	(E.P. & C.o.E., 2002)

Contaminants that may be present in the soil (like heavy metals) can be redistributed when construction work is being executed. Contaminants generally attach to fine sediments rather than large sediments (Laboyrie et al., 2018). It can have a severe influence on water quality and the present receptors nearby. The following contaminants should be determined: Cadmium (Cd), Chromium (Cr), Copper (Cu), Lead (Pb), Mercury (Hg), Nickel (Ni, Zinc (Zn) and oil (OSPAR Commission, 1998).

Quantitative state concept:
The state of the soil quality can be measured through sampling. Sampling provides evidence on the likelihood of the presence of contaminants. The requirements are generally specified by regulators which decide on how many samples should be taken. This depends on historical data. If there is, only a top layer should be investigated. In this layer the pollution of the last couple of years is represented. If there is no historical data, deeper samples should be taken.

According to E.P. and C.o.E. (2002), the concentrations can be calculated at liquid to solids ratio L/S = 2 and 10 l/kg for total release and directly expressed in mg/l for C0 (in the first eluate of percolation test at L/S = 0,1 l/kg). Oil contamination is expressed in mg/kg.

Benchmarking procedure:
The current state can be determined using sampling. Guidelines which provide an indication of the threshold for which feasible effects could occur, should be used. Some countries have their own regulations on this topic, other countries depend on more general guidelines. According to E.P. and C.o.E. (2002), the maximum concentrations can be considered. According to Ministerie van Volkshuisvesting Ruimtelijke Ordening en Milieubeheer (2000), the maximum concentration of oil can be determined.

Summing up the information from the literature, gives the following lists of limit concentrations.

Cadmium (Cd) <0,6 mg/l	Chromium (Cr) <4 mg/l
Copper (Cu) <25 mg/l	Lead (Pb) <5 mg/l
Mercury (Hg) <0,05 mg/L	Nickel (Ni) <5 mg/l
Zinc (Zn) <25 mg/l	Oil <40 mg/kg

Intervention procedure:
Possible intervention measures could be the collection and transport of contaminated soil to specific location for storage or to special soil cleaning plants. This collection and transport could be done by dredgers or excavators.

Evaluation
The maximum contaminants concentration levels can be found that would assure no harm to the present receptors. Sampling before, during and after construction could determine if the desired situation is met.

Results

Figure B.11 shows the elements of the Frame of Reference and their related colors. All the elements can be determined by a reliable source. They are indicated in green.

Sustainability aspect		Strategic objective	Operational objective	Quantitative state concept	Benchmark procedure		Intervention	Evaluation
					Current state	Desired state		
Soil pollutants	3.1 Contaminants							

Figure B.11: Results of operational objective 3.1: Contaminants, in aspect of sustainability: Soil pollutants

B.4. Water consumption

Strategic objective	Source
The water consumption should be reduced to prevent problems due to water scarcity.	(United Nations, 2018)

B.4.1. Operational objective 4.1: Fresh water

Operational objective	Source
The fresh water consumed during production and construction of materials should be minimized.	(United Nations, 2018)

Quantitative state concept:
The volume of freshwater used per ton or m^3 material should be considered.

Benchmarking procedure:
The origin of material can make it difficult to determine the current state. This can be because producers are not always transparent on their water consumption. For regions where fresh water is scare, the importance of reducing water consumption is higher. There is no literature found by the author on a desired state of water consumption.

Intervention procedure:
Smart consumption of water is the solution. In addition, highly consuming water products in water-scarce areas should not be desired. The intervention measures depends on the specific production of the materials and can not be generally approached.

Evaluation
There is no desired state and the current state is location specific. If these values were found or created, evaluation would be possible by comparing these.

Results
Figure B.12 shows the elements of the Frame of Reference and their related colors. The strategic and operational objective, quantitative state concept and evaluation can be determined by a reliable source. They are indicated in green. The current state and intervention can be determined but are project specific and can not be generally approached. That is why it is indicated in yellow. The desired state is not known and indicated in red.

Sustainability aspect		Strategic objective	Operational objective	Quantitative state concept	Benchmark procedure		Intervention	Evaluation
					Current state	Desired state		
Water consumption	4.1 Fresh water							

Figure B.12: Results of operational objective 4.1: Fresh water, in aspect of sustainability: Water consumption

B.5. Noise:

Strategic objective	Source
The quantity of sound should be below levels that will harm present receptors.	(World Bank Group, 2017b)

Noise due to production and construction processes is a sustainability aspect. It causes a disturbance to present receptors. There are different stages of hindrance defined (Royal HaskoningDHV, 2017). The first stage is the audibility to the receptors. The second stage is hindrance in the receptors' ability to respond to its environment. The third level is the Behavioural Threshold (BT). In this stage the receptors are driven off (or attracted). The following stage is the Temporary Threshold Shift (TTS). TTS is a temporary decreased hearing capability. The fifth stage is the Permanent Threshold Shift (PTS). PTS is permanent damage to the hearing system of receptors. The final stage is the Potential Mortal Injury (PMI).

Under noise, two types of noise can be defined: airborne noise and underwater noise.

B.5.1. Operational objective 5.1: Airborne noise

Operational objective	Source
Airborne noise levels should be on average below 53 dB(A) at daytime and 45 dB(A) at nighttime, and maximum of 75 dB(A) at daytime and 65 dB(A) at nighttime.	(World Health Organization, 2018) and (DCMR Milieudienst Rijnmond, 2013a)

Noise nuisance due to construction can have a severe impact on health of local communities. Daily activities at home, at work and during leisure time can be affected. It causes cardiovascular and psycho physiological complications. It could lead to performance reduction and change in social behaviour (World Health Organization, 2018).

Quantitative state concept:
Measuring sounds can be done in decibel following the 'A' weighted method (dB(A)). Airborne sound can be calculated according to the following formula:

$$L_R = L_s + D_C - A \tag{B.1}$$

in which L_R is the sound pressure level at the receptors location in dB(A), L_S is the sound pressure at the source location in dB(A), the parameter D_c is the directive correction in dB(A) and A is the attenuation in dB(A) (Laboyrie et al., 2018). The source sound pressures are generally known for engineering equipment and can be consulted.

Benchmarking procedure:
The current state can be measured with the technique mentioned above but is not known for quay wall projects specifically. In general, it can be said that PTS and PMI should always be avoided and that TTS is undesirable (Royal HaskoningDHV, 2017). The World Health Organization set the guideline for traffic noise on average at 53 dB at daytime and a 45 Db at nighttime (World Health Organization, 2018).

The 'Bouwbesluit 2012' consists of a formal framework for construction and demolition noise in the Netherlands. The 'Circulaire bouwlawaai' contains of descriptive norms for sound levels of construction work during the daytime (07:00 - 09:00) on normal workdays. During weekends and holidays this norm does not apply. In addition, around relevant buildings like schools and hospitals this norm is not applied as well. These norms do not describe actual values. For these reasons, the 'Bouwbesluit' is not applicable and the city of Rotterdam made criteria for acceptable sound levels itself. A collaboration of Ingeniersbureau Gemeentewerken Rotterdam and Milieudienst Rijnmond DCMR developed a set of norms which are applicable in construction and demolition work which has a influence period longer than 1 month and is also applied to housing and schools (DCMR Milieudienst Rijnmond, 2013a). Table B.4 shows the LAr,Lt and maximum sound levels. The Lar,LT is the long time average criteria level and the max. dB(A) is the maximum allowed sound level.

Table B.4: The target values for construction works that take longer than one month determined by Gemeentewerken Rotterdam

Sound level	Day	Evening (19:00-23:00)	Night (23:00-07:00)
Lar,LT	60	55	50
Max. dB(A)	75	70	65

Intervention procedure:

Reducing hindrance could be done by using different engineering equipment with lower source power or changing the construction schedules could reduce the sound levels.

Evaluation

The evaluation procedure can be done by measuring the actual sound levels during the construction, and thereafter comparing these results with the guideline values.

Results

Figure B.13 shows the elements of the Frame of Reference and their related colors. Almost all the elements can be determined by a reliable source. They are indicated in green. However, the current state is indicated in yellow as it is not specifically identified for quay walls development.

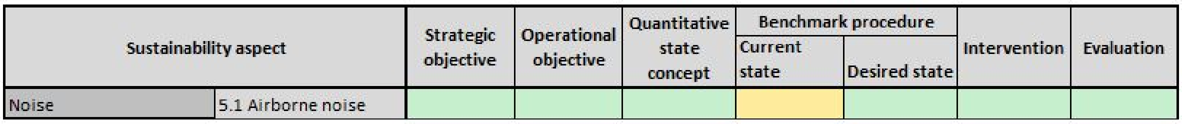


Figure B.13: Results of operational objective 5.1: Airborne noise, in aspect of sustainability: Noise

B.5.2. Operational objective 5.2: Underwater noise

Operational objective	Source
Underwater noise due to construction processes should not harm the animals present in the water	(World Bank Group, 2017b)

The sources of underwater noise are produced by engineering equipment and vessels. Underwater in general, there are continuous human induced sound levels of 90 dB - 100 dB. In the rain, the levels could rise to 110 - 120 dB. A large container vessel could induce a sound level of circa 146 dB, measured on a distance of 100 meter.

Quantitative state concept:

Underwater noise is expressed in dB as well. The attenuation in water depends on many factors like temperature, bathymetry, bottom type, etc. The source wave conducted by engineering equipment and vessels spreads through the water. Two simple approximations are the cylindrical spreading (shallow water) and the spherical spreading (deep water). The sound sources are generally known and can be consulted.

Benchmarking procedure:

The current state can be measured, but it is not specifically identified for quay walls development. The stages PTS and PMI should always be avoided and stage TTS is undesirable. The maximum limits depend on the kind of receptors and their capability to underwater noise. As example Table B.14 shows the different criteria for different types of fish (Royal HaskoningDHV, 2017).

Type of animal	Mortality and potential mortal injury	Impairment	
		Recoverable injury	TTS (Temporary Threshold Shift)
Fish: no swim bladder	>219 dB SEL_{cum} or >213 dB SPL_{peak}	>216 dB SEL_{cum} or >213 dB SPL_{peak}	>>186 dB SEL_{cum}
Fish: swim bladder is not involved in hearing	210 dB SEL_{cum} or >207 dB SPL_{peak}	203 dB SEL_{cum} or >207 dB SPL_{peak}	>186 dB SEL_{cum}
Fish: swim bladder involved in hearing	207 dB SEL_{cum} or >207 dB SPL_{peak}	203 dB SEL_{cum} or >207 dB SPL_{peak}	186 dB SEL_{cum}

Figure B.14: The different type of fish and their related capabilities against underwater noise. Source: (Royal HaskoningDHV, 2017)

Intervention procedure:
A common solution is to start construction with lower levels of underwater noise to scare off animals so they are not present during construction and can't be damaged further. The type of engineering equipment and changing the schedule could reduce underwater noise. A Bubble field is a new technique used to reduce underwater noise.

Evaluation
The evaluation can be done by monitoring the underwater noise during the construction. This should be compared to the resistance dB levels of the present receptors.

Results
Figure B.15 shows the elements of the Frame of Reference and their related colors. Almost all the elements can be determined by a reliable source. They are indicated in green. However, the current state and the desired state are indicated in yellow. The current state is not specifically identified for quay walls development. The desired state depends on the different receptors and is project specific.

Sustainability aspect		Strategic objective	Operational objective	Quantitative state concept	Benchmark procedure		Intervention	Evaluation
					Current state	Desired state		
Noise	5.2 Underwater noise							

Figure B.15: Results of operational objective 5.2: Underwater noise, in aspect of sustainability: Noise

B.6. Waste management

Strategic objective	Source
To ensure that resources remain in use for as long as possible and extract maximum value whilst in use, and be recovered and regenerated at the end of each service life as products and materials that maintain rather than degrade resource value.	(CEEQUAL, 2019)

B.6.1. Operational objective 6.1: Circularity

Operational objective	Source
New constructions will be designed circular and for reuse to achieve a zero-waste economy	(Gladek et al., 2018)

Circularity is part of the new circular economy in which closed material loops are designed. Less waste could reduce costs compared to the present linear economy.

Quantitative state concept:
The percentage of circular product used during the development of quay walls. This percentage is calculated in the design phase and in the end-of-life phase.

Benchmarking procedure:
The possibilities for circularity of current materials are not known and are not included in the design phase. In 2015, the Circular Economy Action Plan was initiated by the European Commission. In this plan, measures are proposed to stimulate Europe's transition towards a circular economy. Greater recycling and re-use will have benefits for both the environment and the economy. The goal of the proposed measures is to "closing the loop" of product life cycles. The revised legislative framework on waste (Directive 2018/851) has entered into force in July 2018. According to this Directive, 80 % of ferrous metals, 30 % of wood, 55 % of plastic should be recycled. More in general, 70 % of packaging waste should be recycled by 2030 (E.P. & C.o.E., 2018b). Related to the construction of quay walls, the steel sheet piles are mostly reused. For concrete, no desired situation is known. That is why the desired situation is not determined for quay wall construction.

Intervention procedure:
The work group 'Circularity in Rotterdam' says that the more valuable the transport of material, water or energy is, the more important it is to close the circle of the material locally. An overview from Gladek et al. (2018):

- Reduction

  Reduction is simplest way to close the circle. A low demand in the material and energy is most convenient when designing the circle system. The demand should not be critical low, endangering the storage of material is not economical feasible anymore. For constructions, this means the improvement of the life cycle of existing quay walls. A second options is to make the deconstruction of quay walls harder by implementing stricter rules. A third option would be a central construction hub. This would reduce the emission due to transport and logistics.

- Synergy

  Synergy aims to create the possibility in exchanging waste streams. A first option would be to close the concrete circle or to reuse the steel sheet piles. Another possibility is to stimulate dismantling instead of deconstruction.

- Production and purchase

  Tendering and contracting circular would reduce the emission.

- Management

  Implementation of a required material passport for all new projects is essential in a circular economy. A second possibility could be the taxation on material instead of on workforce and loans.

Evaluation
If the percentage reusable material is known in a standard quay wall, it can be compared to a desired percentage.

Results
Figure B.16 shows the elements of the Frame of Reference and their related colors. The strategic objective, quantitative state concept and evaluation procedure are defined and are indicated in green. There is an operational objective determined, however a real operational action can not be found for the most present materials in a quay wall. The intervention measures are proposed, although their impact is not known. These elements are indicated in yellow. The current state and the desired state of the most present materials in quay wall development are not defined.

Sustainability aspect		Strategic objective	Operational objective	Quantitative state concept	Benchmark procedure		Intervention	Evaluation
					Current state	Desired state		
Waste management	6.1 Circularity							

Figure B.16: Results of operational objective 6.1: Circularity, in aspect of sustainability: Waste management

B.7. Energy

Strategic objective	Source
Energy should be renewable	(United Nations, 2018)

The generation of energy requires fuels or electricity. Grey electricity and fossil fuels emit toxic combustion gases and GHG. This has been described in aspect 'Air pollutants'. Renewable energy causes lower emission of these gases and is an intervention method. But in literature, renewable energy is also seen as a goal in itself. This will be handled in this aspect.

B.7.1. Operational objective 7.1: Renewable energy

Operational objective	Source
At least 32% of the total energy should be generated renewable in 2030 in the E.U.	(E.P. & C.o.E., 2018a)

Quantitative state concept:
The percentage of renewable energy should be calculated. Under renewable energy, all energy is meant that originates from sources that are inexhaustible in duration but have the disadvantage of being capacity-limited. The major types of renewable energy are biomass, hydropower, geothermal heat, wind energy and solar energy.

Benchmarking procedure:
At the moment, the use of green electricity in quay wall design is negligible. In December 2018, the new revised Renewable Energy Directive (E.P. & C.o.E., 2018a) entered into force. It establishes a new binding renewable energy target for the EU for 2030 of at least 32%. This means that of the total energy, 32% should be generated renewable.

Intervention procedure:
Intervention measures could be to electrify engineering equipment which uses renewable energy. Fuels like hydrogen and ammonia, generated with renewable energy, can be used as well.

Evaluation
The evaluation procedure can be done by comparing the percentages of the current situation and the desired situation.

Results
Figure B.17 shows the elements of the Frame of Reference and their related colors. All the elements can be determined by a reliable source. They are indicated in green.

Sustainability aspect		Strategic objective	Operational objective	Quantitative state concept	Benchmark procedure		Intervention	Evaluation
					Current state	Desired state		
Energy	7.1 Renewable							

Figure B.17: Results of operational objective 7.1: Renewable energy, in aspect of sustainability: Energy

B.8. Light pollution

Strategic objective	Source
Reduction of night time light pollution to levels that do not interact with present receptors.	(BREEAM, 2014), (Pawson & Bader, 2014)

Light pollution increases the ambient light level of the night sky. Excessive designed outdoor lighting sends unnecessary light into adjacent areas. Inefficient lighting also consumes more power, but this is an intervention to reduce energy. This is not been described further.

B.8.1. Operational objective 8.1: Light

Operational objective	Source
-	-

Recognition of the impact of nighttime light pollution on natural ecosystems is increasing. However, an operational objective is not found by the author. According to research from Pawson and Bader (2014), the change from "yellow" high-pressure sodium vapor lamps (HPS) to new 'white' light-emitting diodes (LEDs) has a greater ecological impact. They warn that the large-scale adaption to efficient LED lightening could cause a larger ecological impact. They ask for collaborative research between ecologists and electrical engineers to minimize potential ecological effects of LED light.

Quantitative state concept:
The primary unit of measure in photometry is lumen (lm), which is a measure of light perceived by the human eye. A lux (lx) is an unit of illumination equal to 1 lumen per square meter and the candela (cd) is the basic SI unit of luminous intensity. In addition, the temperature and color of the light may have an influence as well. Further research is required.

Benchmarking procedure:
The current state can be defined with the above mentioned parameters. However, the impact on the biodiversity and which receptors are influenced by this aspect is not defined yet. There is no desired state found in the literature on light pollution and its impact on ecological environment.

Intervention procedure:
Because the causes are not defined yet, intervention measures are not known.

Evaluation
The evaluation procedure is difficult to define if the system is not understand yet. Further research should be done first into this aspect.

Results
Figure B.18 shows the elements of the Frame of Reference and their related colors. The strategic objective is defined and indicated in green. The indicators of the current state are known, however the influenced receptors are not. It is indicated in yellow. The remaining elements are not defined and indicated in red.

Sustainability aspect		Strategic objective	Operational objective	Quantitative state concept	Benchmark procedure		Intervention	Evaluation
					Current state	Desired state		
Light pollution	8.1 Light							

Figure B.18: Results of operational objective 8.1: Light, in aspect of sustainability: Light pollution

B.9. Biological ecosystem

Previous Paragraphs of this Appendix have described various operational objectives that have an influence on the conservation of the biological ecosystems. The objectives on emission of toxic pollutants in water, soil and air, airborne and underwater noise, and light pollution, does relate to the biological ecosystems. Although, there is not a operational objective described yet on preservation. That will be discussed here.

Strategic objective	Source
Respect the biological ecosystems	(United Nations, 2018)

B.9.1. Operational objective 9.1: Ecosystems

Operational objective	Source
Conservation of the biological ecosystems at the production and construction sites	(CEEQUAL, 2019)

Quantitative state concept:

Two methods are defined to calculate the biological ecosystems, namely in quantitative terms or in the qualitative terms. The first method calculates the number of different species in the area and shows the most counted species. The second method counts the different species and valuate them. This has the advantage that the rareness of species can be taken into account besides the number of species. Both method acquire field observations.

Benchmarking procedure:

The current situation can be measured as mentioned above. For the desired situation, important biological ecosystems are written down and protected. For example, Natura 2000 is a network of nature protection areas in the territory of the European Union. It consists of Special Areas of Conservation and Special Protection Areas designated respectively under the Habitats Directive and Birds Directive. In this area, preservation of biological ecosystems is regulated. If the quay wall project is located in a protected area, desired targets are not found by the author.

Intervention procedure:

Interventions could be the conservation of the biological ecosystem. If this is not possible, mitigation measures or even new creation somewhere nearby could be an option. Some measures are defined and possible on commercial scale (e.g. Econcrete), other possible measures are still in research phase. Their impact is not always known.

Evaluation

The evaluation procedure would be to compare the current situation with the desired situation. This could be done with field observations during the construction and after the construction. The procedure is project specific.

Results

Figure B.19 shows the elements of the Frame of Reference and their related colors. The strategic and operational objective, the quantitative state concept, the current state and evaluation are defined and indicated in green. The remaining elements are indicated in yellow. The desired state is defined for protected location, but not for unprotected locations. Interventions measures are proposed, but their impact is not always determined. Some are still in research phase.

Sustainability aspect		Strategic objective	Operational objective	Quantitative state concept	Benchmark procedure		Intervention	Evaluation
					Current state	Desired state		
Biological ecosystem	9.1 Ecosystems							

Figure B.19: Results of operational objective 9.1: Ecosystems, in aspect of sustainability: Biological ecosystem

B.10. Employment safety

Strategic objective	Source
Employment during the production and construction should always be safe.	(World Bank Group, 2017b)

B.10.1. Operational objective 10.1

Operational objective	Source
The number of incidences should be equal to zero	(Ministerie van Sociale Zaken en Werkgelegenheid, 2010)

Employment safety is present through all the phases of the development of a quay wall. A quay wall should be designed in such a way that it minimizes the chances of incidences. The construction, maintenance and end-of-life phase should follow regulations that minimizes the chances of incidences.

Quantitative state concept:
The number of incidences can be calculated. Under incidences, all events that should be written down according to the Arbowet, are considered. In the Arbowet, the criteria are described for safe employment. In addition, professional expertise can be consulted to check every action plan.

Benchmarking procedure:
The current state is written down and controlled by safety experts. However, production location in other countries is more difficult to control. The desired state for employment safety is to aim at zero incidences.

Intervention procedure:
To achieve the desired state, guiding, protocols, training and other safety measures should be incorporated in every step in the development of a quay wall. However, the safety of employment is partly a human error and difficult to prevent 100 %.

Evaluation
The evaluation procedure is done by safety experts working at the authority. They should check the safety reports and steer the projects to be safe.

Results
Figure B.20 shows the elements of the Frame of Reference and their related colors. Almost all the elements are indicated in green. The current state is indicated in yellow, because the control in production location can be seen as an obstacle. The intervention is indicated in yellow as well. A 100 % safe construction and production site is not found yet.

Sustainability aspect		Strategic objective	Operational objective	Quantitative state concept	Benchmark procedure		Intervention	Evaluation
					Current state	Desired state		
Employment	10.1 Safety							

Figure B.20: Results of operational objective 10.1: Safety, in aspect of sustainability: Employment

B.11. Cultural

Strategic objective	Source
Cultural aspects should be keeping its value.	(World Bank Group, 2017b)

Cultural value consists of the landscape and the archaeological value of the area in which the quay wall is developed. Assumed is that quay walls are always developed in a port area. The aesthetically value of a quay wall is always a contribution to a port area. That's why it falls out of scope. The archaeological value will be discussed further.

B.11.1. Operational objective 11.1: Archaeology

Operational objective	Source
Archaeological heritage found during construction should be kept reserved	(World Bank Group, 2017b)

Quantitative state concept:
During pre-construction measurements (like sampling) and during construction, part of wrecks or old building can be found. If this occurs, an archaeological research should be performed.

Benchmarking procedure:
The current situation is checked during the measurements and/or during construction. In general, desired is that archaeological findings should be kept reserved.

Intervention procedure:
If the presumption is that there is a high chance of archaeological findings, some sampling and test can be performed to check possible findings.

Evaluation
The evaluation procedure is to ensure that the archaeological findings are kept reserved.

Results
Figure B.21 shows the elements of the Frame of Reference and their related colors. All the elements can be determined by a reliable source. They are indicated in green.

Sustainability aspect		Strategic objective	Operational objective	Quantitative state concept	Benchmark procedure		Intervention	Evaluation
					Current state	Desired state		
Cultural	11.1 Archaeology							

Figure B.21: Results of operational objective 11.1: Archaeology, in aspect of sustainability: Cultural

B.12. Future resilience

Strategic objective	Source
The design of the quay wall should be resilient for future changes.	(Duurzaam GWW, 2018)

Future uncertainties like global warming, different vessels and different terminal functions should be considered when designing a quay wall. In operational objective 12.1, floods due to sea level rise and weather changes are considered. In operational 12.2, future alterations in vessel sizes and cargo dimensions are taken into account.

B.12.1. Operational objective 12.1: Floods

Operational objective	Source
The height of port infrastructures should be increased corresponding an acceptable chance of flooding.	PoR expert

With an increasing sea level and more sever storms, the chance of floods will increase. Floods may cause economic damage, environmental damage, casualties and societal disruption.

Quantitative state concept:
The indicators are the height of the quay walls, the wave heights of future storms and the acceptable chance of flooding. A first step is to determine the acceptable chance of floodings. Using predicted storm surges for the coming 100 years, storm surge height can be determined and the height of the quay wall can be calculated.

Benchmarking procedure:
The current state can be calculated. The desired state depends on the area's economical and social situation. In the Rotterdam port area, the acceptable chance of floodings is 1/4000 (Tretjakova, 2013).

Intervention procedure:
Intervention measures can be done by increasing the height of the quay wall.

Evaluation
If the desired height of the quay wall is determined, it can be calculated what the flooding chance is. This should be below the acceptable change of floodings.

Results
Figure B.22 shows the elements of the Frame of Reference and their related colors. All the elements can be determined by a reliable source. They are indicated in green.

Sustainability aspect		Strategic objective	Operational objective	Quantitative state concept	Benchmark procedure		Intervention	Evaluation
					Current state	Desired state		
Future resilience	12.1 Floods							

Figure B.22: Results of operational objective 12.1: Floods, in aspect of sustainability: Future Resilience

B.12.2. Operational objective 12.2: Adaptability

Operational objective	Source
The design of port infrastructure should be adaptable for future changes in vessels and cargo sizes	PoR expert

Ship sizes and cargo loads change over time. Instead of designing port infrastructure for today, port infrastructure for tomorrow should be designed.

Quantitative state concept:
This is done by looking at the trends in future shipping dimensions and cargo sizes. This will influence the draught and strength and will change the dimensions of the quay wall design.

Benchmarking procedure:
In general, for barges the draught will not change much due to dependency on the depth of hinterland navigation waterways. For sea vessels, container ship vessels are still increasing. CEMT VIb ships have a draught of 2.5 - 4 meter which are the largest draught for inland vessels in Trans-European Inland Waterway network. It is not expected that inland vessels will develop to larger draught due to waterways' natural depth boundaries. The loads due to larger cranes should be considered as well.

Intervention procedure:
It should be designed with an eye on tomorrow. Over-dimensioning could prepare the quay wall for uncertainties. Examples are a deeper draught and easy adaptability of quay wall using second anchoring.

Evaluation
In general, the future trend should be consulted and acted upon. The intervention of overdimensioning of quay walls to reduce the impact of uncertainties, sounds comprehensible, but increases the amount of materials used and the related environmental impact. Evaluation is difficult due to the uncertainty.

Results
Figure B.23 shows the elements of the Frame of Reference and their related colors. Most of the elements can be determined by a reliable source. They are indicated in green. However the operational objective, desired state and the evaluation are defined, but due to the uncertainties, assumed not directly usable by the author. That is why it is indicated in yellow.

Sustainability aspect		Strategic objective	Operational objective	Quantitative state concept	Benchmark procedure		Intervention	Evaluation
					Current state	Desired state		
Future resilience	12.2 Adaptability							

Figure B.23: Results of operational objective 12.2: Adaptability, in aspect of sustainability: Future Resilience

B.13. Traffic management

Strategic objective	Source
The traffic induced by the development of the quay wall, should be managed sustainable.	(CEEQUAL, 2019)

During the development of a quay wall, traffic management is essential. In this aspect, the resilience of traffic and the hindrance caused by traffic is considered.

B.13.1. Operational objective 13.1: Resiliency

Operational objective	Source
Hours per working day that the production or construction site is not reachable should be equal to zero.	(CEEQUAL, 2019)

The traffic network should be resilient. This means that the production and construction site should be reachable.

Quantitative state concept:
The resiliency can be expressed in hours per working day that the production or construction site is not reachable. This can be calculated using models and tools that predict traffic intensity. However, the models only predict and will not be 100 % representative to the actual situation.

Benchmarking procedure:
The current state can be found by managers' observations. The desired state is that the production and construction site should be reachable during working hours.

Intervention procedure:
Possible intervention measures include providing multiple transport possibilities from and to the construction location. The measures are project specific.

Evaluation
The evaluation procedure is observed by the project managers that compare the current situation with the desired situation.

Results
Figure B.24 shows the elements of the Frame of Reference and their related colors. Most of the elements can be determined by a reliable source. They are indicated in green. However the models used in the quantitative state concept are not expected to be completely representative to the actual situation. It is indicated in yellow.

Sustainability aspect		Strategic objective	Operational objective	Quantitative state concept	Benchmark procedure		Intervention	Evaluation
					Current state	Desired state		
Traffic management	13.1 Resiliency							

Figure B.24: Results of operational objective 13.1: Resiliency, in aspect of sustainability: Traffic management

B.13.2. Operational objective 13.2: Hindrance

Operational objective	Source
Hours per working day that the construction-induced traffic exceeds the carrying capacity of the local road network should be equal to zero.	(CEEQUAL, 2019)

Quantitative state concept:
Hours per working day that the traffic exceeds the carrying capacity of the local road network. Traffic models and tools can be used to predict traffic intensity. The representative of these models is assumed not to be 100 %.

Benchmarking procedure:
The current situation can be determined. The desired state is that the capacity of the road network should not be exceeded.

Intervention procedure:
Intervention measures for personnel could be the application of busses and the promotion of carpooling. Flexible working hours could also be implemented. For material transport, modal transport of material to the construction site can be considered.

Evaluation
The evaluation procedure is observed by the project managers that compare the current situation with the desired situation.

Results
Figure B.25 shows the elements of the Frame of Reference and their related colors. Most of the elements can be determined by a reliable source. They are indicated in green. However the models used in the quantitative state concept are not expected to be completely representative to the actual situation. It is indicated in yellow.

Sustainability aspect		Strategic objective	Operational objective	Quantitative state concept	Benchmark procedure		Intervention	Evaluation
					Current state	Desired state		
Traffic management	13.2 Hindrance							

Figure B.25: Results of operational objective 13.2: Hindrance, in aspect of sustainability: Traffic management

B.14. Stakeholder involvement

Strategic objective	Source
Stakeholders should be informed and able to participate in the project.	(Duurzaam GWW, 2018)

Stakeholders is the group including all the organizations, companies, people, etc that are in one way or another connected to the development of a quay wall.

B.14.1. Operational objective 14.1: Stakeholders

Operational objective	Source
Stakeholder involvement should be given focus during the decision making, while at the same time for each subject matter, infiltrating the weight of each stakeholders‘ opinion	(Duurzaam GWW, 2018)

In the development of a quay wall, the quantity of stakeholders is assumed to be low. This is because it is only a part of the total port planning, which comprises various stakeholders. Stakeholders participation is important for projects to be developed. In general, the following can be said about stakeholders.

Quantitative state concept:
Through questionnaires, stakeholders can give their opinion as well as their experienced involvement level.

Benchmarking procedure:
The current situation can be determined. it is desired that all stakeholders should be at least contacted to give them the possibility to get involved.

Intervention procedure:
Possible interventions methods are questionnaires and sessions with stakeholders.

Evaluation
The evaluation procedure can be done by questionnaires with the stakeholders to see if they felt included in the decision making.

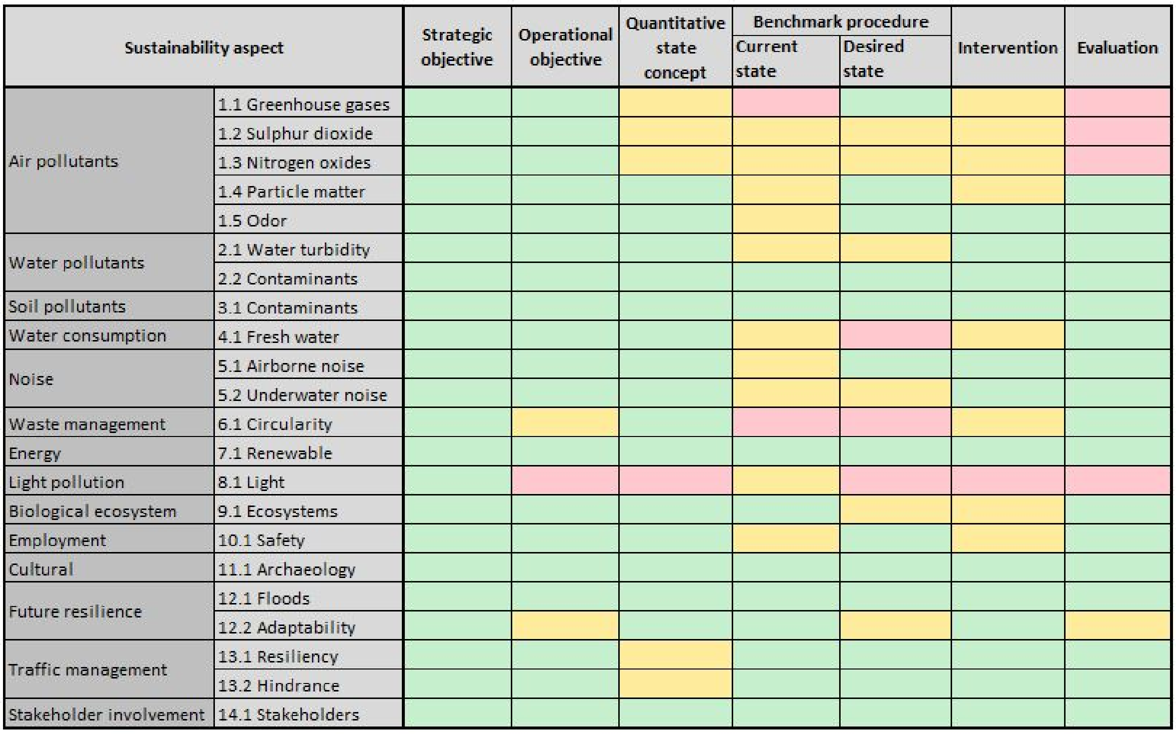
Results
Figure B.26 shows the elements of the Frame of Reference and their related colors. All the elements can be determined by a reliable source. They are indicated in green.

Sustainability aspect		Strategic objective	Operational objective	Quantitative state concept	Benchmark procedure		Intervention	Evaluation
					Current state	Desired state		
Stakeholder involvement	14.1 Stakeholders							

Figure B.26: Results of operational objective 14.1: Stakeholders, in aspect of sustainability: Stakeholder involvement

B.15. Results

Figure B.27 shows the results of the fourteen aspects of sustainability implemented in the Frame of Reference.



Sustainability aspect		Strategic objective	Operational objective	Quantitative state concept	Benchmark procedure		Intervention	Evaluation
					Current state	Desired state		
Air pollutants	1.1 Greenhouse gases							
	1.2 Sulphur dioxide							
	1.3 Nitrogen oxides							
	1.4 Particle matter							
	1.5 Odor							
Water pollutants	2.1 Water turbidity							
	2.2 Contaminants							
Soil pollutants	3.1 Contaminants							
Water consumption	4.1 Fresh water							
Noise	5.1 Airborne noise							
	5.2 Underwater noise							
Waste management	6.1 Circularity							
Energy	7.1 Renewable							
Light pollution	8.1 Light							
Biological ecosystem	9.1 Ecosystems							
Employment	10.1 Safety							
Cultural	11.1 Archaeology							
Future resilience	12.1 Floods							
	12.2 Adaptability							
Traffic management	13.1 Resiliency							
	13.2 Hindrance							
Stakeholder involvement	14.1 Stakeholders							

Figure B.27: Results of the fourteen aspects of sustainability implemented in the Frame of Reference.

C

Interviews with PoR personnel and contractors

C.1. Interviews with PoR personnel

	Name: Sr. General Management Score: 0-3	Name: Sr. Finance Score: 0-3	Name: Sr. PoR-PD Score: 0-3	Name: Sr. PoR-EM Score: 0-3	
Accessibility	2	1	3	1	1.75
Area quality	2	2	2/3	1	1.88
Ecology	2	3	1,5	3	2.38
Energy	3	3	1	2	2.25
Health	3	3	3	2	2.75
Investment climate	2	1	3	1	1.75
Materials	3	3	1	3	2.5
Social relevance	2	1	1/2	1	1.15
Soil	2	3	2	2	2.25
Water	2	3	2	2	2.25
Area usage	2	2	3	1	2
					Avg. = 2.10

Figure C.1: Interviews with PoR personnel

Table C.1: Changes of the terms of the interviews

Term used in interview	Corresponding aspect of sustainability according to Chapter 2
Accessibility	Traffic management
Area quality	Cultural
Ecology	Biological ecosystems, Underwater noise
Energy	Greenhouse gases
Health	Air pollutants (excluding greenhouse gases), Airborne noise, Employment safety
Investment climate	-
Materials	Waste management
Social relevance	Stakeholder analyses
Soil	Soil pollutants
Water	Water pollutants, Water Consumption
Area usage	Future resiliency

C.2. Interview contractors

Two interviews are conducted with contractors Royal Van Oord and Royal Boskalis Westminster N.V. . The purpose of these interviews was to achieve a general opinion on sustainability in infrastructure construction from another perspective. Most information of this interview intertwined with literature and the conducted exercise. That's why the full interviews are not shown. However, some interesting statements are written down:

- 'If authorities don't steer on reduction of GHG emission, the input we can deliver to reduce is small. We are competing with other companies, which makes including GHG emission reduction , if not asked, difficult.'
- Authorities are not always clear on what the actually want to achieve. A lower MKI doesn't automatically decreases the GHG emission. However, the authorities do want to achieve a lower GHG emission.'
- 'Some GHG emission values in DuboCalc are outdated, hence wrong in the present time. We have our own LCA, hence the right value. If our values are lower, we use them. However, if the values are higher that the DuboCalc value, we can use the DuboCalc value, although this isn't correct'

D Quantification tool

D.1. Advantages and disadvantages of DuboCalc

Table D.1: Table with the advantages and disadvantages of DuboCalc

Advantage	Source	Disadvantage	Source
The tool reduces the time to make CO_2 calculations by offering various infrastructure objects. [1]	(de Vos, 2016), (van Driel, 2017)	The database behind DuboCalc does not cover the full spectrum of infrastructure objects [4]	(de Vos, 2016), conducted interviews (Appendix C.2)
The tool prevent excessive administration compared to individual LCA's.[2]	(de Vos, 2016)	Circularity is hard to include and causes findings that are contradicting with common sense. [5]	(de Vos, 2016)
Relative simpleness of working with the tool. [3]	(Duurzaam GWW, 2019)	Fixed values for transport distances. [6]	(de Vos, 2016), conducted interviews (Appendix C.2)
		Knowledge about quay wall is required [7]	own observation

Explanation of the advantages and disadvantages.

1. Normally the tender period is too short to calculate specific LCA's of materials. By selecting various objects from the database, an average value can be found (de Vos, 2016).

2. Determining specific LCA for objects of every project will cause excessive administration work. Using the DuboCalc tool will reduce the work (de Vos, 2016).

3. The tool is a straightforward method with only some alteration per object possible (Duurzaam GWW, 2019). This makes it a relative simple tool.

4. From the conducted interviews with contractors (Appendix C.2) and the report of (de Vos, 2016), it can be said that the database does not cover the full spectrum of infrastructure objects.

5. Circularity is taken into account in DuboCalc, although there are some remarks. DuboCalc does not have various recycling options. Instead it has one option. The raises the following concern: for some objects, a lower environmental reduction will be reached when a product is turned into a waste product which can be used only one time. An example of this is concrete: when concrete is turned into granulate, the product is de-valued and can only be used once. The life cycle stops here. The danger is that is not seen because for an individual project, de-valuing the product has a positive outcome for sustainability, but during a series of projects it has not.

   Secondly, from own experience the option like Azobé wood has an overall positive influence on the emission. Using less material will result in more CO2-eq emission. This contradicts with common sense when using less material, less CO2eq is emitted.

6. DuBoCalc has fixed values for transport distances for various materials. This is to stop 'creative' administration from constructors. Transport distances have an influence on material choice and should better be changeable. In addition, costs and transport optimization (in terms of sustainability) don't always go together. With a lower sailing speed, the emission can be reduced although the construction will take a longer time. This can not be added into DuboCalc.

7. In the exercise made in this report, various mistakes were made concerned basic quay wall construction. It can be concluded that knowledge on quay walls is required.

D.2. Tender offer (Dutch)

Port of Rotterdam

Memo
Openbaar

Aan	
Van	Bosschieter, Caroline - POR\PD\PE Van Rhede van der Kloot, Godert - POR\PD\PE (Graduate student)
Kopie aan	
Onderwerp	**Uitvraag C02/MKI berekening kademuur met DuboCalc**
Actie	

Doel:
Het inzichtelijk krijgen van de representativiteit van DuboCalc m.b.t. de MKI berekeningen van kademuren. Verschillende I-bureaus krijgen dezelfde inputgegevens waarvan gevraagd wordt ze te gebruiken voor het berekenen van MKI waarden (waaronder de CO2e footprint). De uitkomsten en aannames worden vergeleken om de bandbreedte van de uitkomsten te observeren en het uitvraagdocument te verbeteren.

Scope:
- De MKI (en een aparte focus op CO2eq) van een 100m strekkende meter binnenvaartkade.

Gegevens:
- Design en constructie gegevens van een kademuur van 479,94 meter: vermeld in de bijlage.
- Levensduur: 100 jaar.
- Gebruik van DuboCalc 5.1.0 en library versie: 6.01.27092018 volgens ‘Bepalingsmethode Milieuprestatie Gebouwen en GWW-werken 3.0’ en de vaste waarden uit de nationale milieudatabase (geen eigen waarden van materialen).
- Kathodische bescherming en bemaling worden niet meegenomen in de berekeningen.

Verwachte resultaten zijn:

1. Resultaten van de MKI en extra apart vermeld de CO2eq. Dit uitgesplitst in de verschillende werkzaamheden, levenscyclusfases en materialen. Maak gebruik van grafieken en tabellen. Rapporteer de **volledige** MKI berekeningen.

2. Een overzicht van de aannames en inschattingen die gemaakt zijn. Rapporteer welke opties voor het ontwerp in DuboCalc missen en welke opties daar worden voor aangenomen. Vermeld tekortkomingen in de nationale milieudatabase.

3. Rapporteer van welke opties uit DuboCalc een gerichtere LCA opgesteld dient te worden en wat het verwachte effect op de MKI is.

4. Advies over mogelijke reducties van de MKI-waarde en CO2eq in het ontwerp en/of constructie proces.

Datum 14-06-2019

Meenemen in DuboCalc berekening (checklist):

- Zand / grond verzet
- Beton
- Staal
  - wapeningsstaal
  - (Tijdelijke) damwanden / buispalen / groutankers
- Baggerwerkzaamheden
- Bodembescherming

Vragen?

Voor vragen of opmerkingen over deze uitvraag kunt u mij mailen op gp.rhede.van.der.kloot@portofrotterdam.com of bellen op 06 83568828.

Port of Rotterdam

Datum 14-06-2019

Bijlage: Design

Binnenvaartkade:

Binnenvaartkademuur met een lengte van **479,94 meter** met een levensduur van **100 jaar**.

Werkvoorbereiding
Tijdens de werkvoorbereiding worden de volgende werkzaamheden uitgevoerd: grondwerk, ontgraven, aanbrengen, profileren en vervoer van en naar tijdelijke depot en verwerken in depot.

Grondverzet:
Over de totale lengte wordt er eerst 9.941 m^3 grond aangevuld uit een depot (transportafstand van 200 meter). Later wordt er 29.898 m^3 zand ontgraven uit de bouwput (een transportafstand van 200 meter)

Bouwkuip:
Over de totale lengte worden er tijdelijke damwanden PU18 (128,2 kg/m^2) met een lengte van 10 meter geplaatst en uiteindelijk ook verwijderd.

Constructiewerkzaamheden:

Verankering:
159 verankeringen worden er geplaatst over de totale lengte. Aangenomen is dat één groutanker bestaat uit 3 m^3 grout en dat één ankerstang 45 m lang is.

Wapening:
De wapening van de constructie bestaat uit 786 ton betonstaal over de hele lengte.

Betonconstructie:
Betonmortel C35/C45 CEMIII wordt gebruikt. Het volume is gelijk aan 4.649 m^3 voor de gehele lengte.

Combiwandconstructie:
De combiwand bestaat uit: 157 buispalen met een totale massa van 1.676,76 ton (met een lengte 29 meter, een doorsnede van 1067 mm en een massa van 10,68 ton per buispaal) en stalen damwanden met een totale massa van 537,7 ton (PU18, lengte van 14,7 meter).

Bodembescherming:
Er is 1600 ton aan breuksteen (afstand 50 km) en 35.768 ton aan hergebruikte steen (afstand 1 km) en 11.720 ton hergebruikte steen (afstand 10 km) gebruikt voor de volledige lengte van de kademuur.

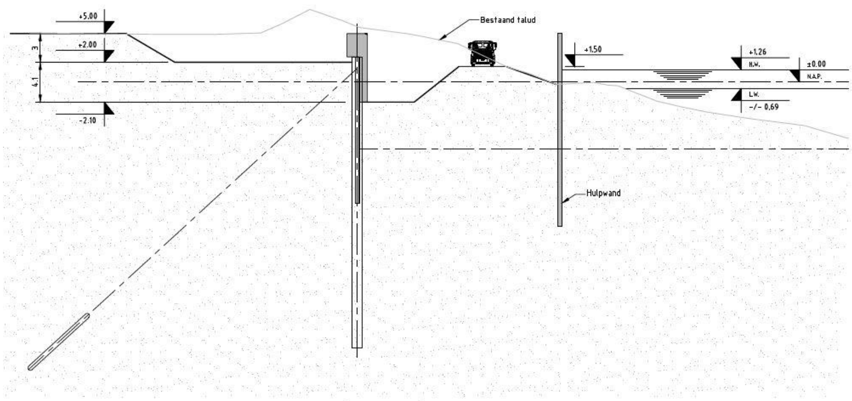
Port of Rotterdam

Datum 14-06-2019

Baggerwerkzaamheden:

Deze fase betreft het afvoeren en baggeren van zand en slib. Er is 28.641 m^3 aan slib te baggeren en 97.511 m^3 aan zand te baggeren. Hiervoor is 226,6 ton aan brandstof verbruikt (met een sleephopperzuiger: brandstof is MDO en een transportafstand van 200 meter). Dit is voor de volledige lengte van de kademuur.

Afbeelding:



DOORSNEDE: BINNENVAARTKADE (ZUIDZIJDE)
(schaal 1:250)

Inputgegevens van de KB:

131 400 kWh per jaar voor de volledige strekkende kademuur. Er wordt gebruik gemaakt van grijze elektriciteit.

D.3. Results of objectivity research

D.3.1. Input of the different companies: results

Input values for 479,94 m quay wall		Results 1					Results 2			
Action:	Unit A/B/C/D	Company A	Company B	Company C	Company D	Unit A/B/C/D	Company A	Company B	Company C	Company D
Soil backfilling	m3/m3/m3/m3	9.941	9.940	9.941	9.941	m3/m3/m3/m3	9.941	9.940	9.941	9.941
Soil excavation	m3/m3/m3/m3	29.898	29.900	29.898	29.898	m3/m3/m3/m3	29.898	29.900	29.898	29.898
Sheet piles temporary	ton/ton/ton/ton	615	1.003	615	615	ton/ton/ton/ton	615	614	615	615
Anchorage 1	m3/m3/m3/m3	159	475	477	477	m3/m3/m3/m3	477	475	477	477
Anchorage 2	/ /m/	-	-	7.155	-	ton/m/m/	75	34.340	7.155	-
Rebar	ton/ton/ton/ton	786	787	786	786	ton/ton/ton/ton	786	787	786	786
Concrete	m3/m3/m3/m3	4.649	9.940	4.649	4.649	m3/m3/m3/m3	4.649	4.651	4.649	4.649
Steel piles	ton/ton/ton/ton	1.677	1.675	1.677	1.677	ton/ton/ton/ton	1.677	1.675	1.677	1.677
Steel sheet piles	ton/ton/ton/ton	538	538	538	538	ton/ton/ton/ton	538	538	538	538
Bed, bank and shore protection (1)	/ton/ton/ton	*	1.598	1.600	1.600	/ton/ton/ton	*	1.598	1.600	1.600
Bed, bank and shore protection (2)	/ton/ton/ton	*	35.770	35.768	35.768	/ton/ton/ton	*	35.770	35.768	35.768
Bed, bank and shore protection (3)	/ton/ton/ton	*	11.821	11.720	11.720	/ton/ton/ton	*	11.821	11.720	11.720
Dredging	m3/l/m3/l	126.152	226	126.152	227	l/l/m3/l	226	226	126.152	227
ICCP	/kWh/kWh/kWh	*	13.139.797	13.140.000	13.140.000	/kWh/kWh/kWh	*	13.140.000	13.140.000	13.140.000

Figure D.1: Input of the different companies: results

D.3.2. Choice of DuboCalc object by the different companies: results

Object choice of DuboCalc object	Results 1				Results 2:			
Action:	Company A	Company B	Company C	Company D	Company A	Company B	Company C	Company D
Soil backfilling	Ground per axle	Ground per axle	Ground per axle	Ground per axle	Ground per axle	Ground per axle	Ground per axle	Ground per axle
Soil excavation	Land sand per axle (Released)	Work with work: sand	Land sand per axle (Released)	Ground per axle	Land sand per axle (Released)	Work with work: sand	Land sand per axle (Released)	Ground per axle
Sheet piles temporary	Sheet piles temporary + 1 x Released	Sheet piles temporary	Sheet piles temporary	Sheet piles temporary	Sheet piles temporary	Sheet piles temporary	Sheet piles temporary	Sheet piles temporary
Anchorage 1	Anchorage mortar	Anchorage mortar	Anchorage mortar	Anchorage mortar	Anchorage mortar	Anchorage mortar	Anchorage mortar	Anchorage mortar
Anchorage 2	-	-	Steel pile small	-	Rebar	Steel pile small	Steel pile small	-
Rebar	Rebar	Rebar	Rebar	Rebar	Rebar	Rebar	Rebar	Rebar
Concrete	Concrete mortar C35/C45 CEMIII	Concrete mortar C35/C45 CEMIII	Concrete mortar C35/C45 CEMIII	Concrete mortar C35/C45 CEMIII	Concrete mortar C35/C45 CEMIII	Concrete mortar C35/C45 CEMIII	Concrete mortar C35/C45 CEMIII	Concrete mortar C35/C45 CEMIII
Steel piles	Driving pile (steel)	Steel pile large	Driving pile (steel)	Driving pile (steel)	Driving pile (steel)	Driving pile (steel)	Driving pile (steel)	Driving pile (steel)
Steel sheet piles	Steel sheet piles	Steel sheet piles	Steel sheet piles	Steel sheet piles	Steel sheet piles	Steel sheet piles	Steel sheet piles	Steel sheet piles
Bed, bank and shore protection (1)	*	Rubble stone	Rubble stone	Rubble stone	*	Rubble stone	Rubble stone	Rubble stone
Bed, bank and shore protection (2)	*	Reused rocks	Reused rocks	Reused rocks	*	Reused rocks	Reused rocks	Reused rocks
Bed, bank and shore protection (3)	*	Reused rocks	Reused rocks	Reused rocks	*	Reused rocks	Reused rocks	Reused rocks
Dredging	Work with work: sand from dredging	MDO	Maintenance dredging (TSHD type)	MDO	MDO	MDO	Maintenanc e dredging (TSHD type)	MDO
ICCP	*	Electricity grey	Electricity grey	Electricity grey	*	Electricity grey	Electricity grey	Electricity grey

Figure D.2: Choice of DuboCalc object by the different companies: results

D.3.3. Output of the different companies: results

CO2-eq emission in kg	Results 1				Results 2:			
Action:	Company A	Company B	Company C	Company D	Company A	Company B	Company C	Company D
Soil backfilling	251.686	19.000	18.505	18.505	18.505	19.000	18.505	18.505
Soil excavation	32.228	60.000	35.075	55.655	32.228	60.000	35.075	55.655
Sheet piles temporary	7.771	63.000	38.794	38.794	38.793	39.000	38.794	38.794
Anchorage	15.552	47.000	74.511	46.799	105.791	380.000	74.511	46.799
Rebar	184.793	185.000	184.787	184.791	184.793	185.000	184.787	184.791
Concrete mortar	254.232	544.000	254.247	254.247	254.232	254.000	254.247	254.247
Steel piles	334.253	1.673.000	334.723	334.723	334.253	335.000	334.723	334.723
Steel sheet piles	132.118	132.000	132.111	132.111	132.118	132.000	132.111	132.111
Bed, bank and shore protection	80.000	80.000	79.868	79.868	80.696	80.000	79.868	79.868
Dredging	135.982	177.000	198.338	177.049	186.603	177.000	198.338	177.049
ICCP	2.308.521	1.780.000	2.308.521	2.308.521	2.308.521	2.278.000	2.308.521	2.308.521
Total	3.737.135	4.760.000	3.659.482	3.631.064	3.676.533	3.939.000	3.659.482	3.631.064

Figure D.3: Output of the different companies: results

D.4. DuboCalc objects translation list

Translate objects from English to Dutch	
English	Dutch
Ground per axle	Grond (per as)
Land sand per axle (Released)	Landzand per as (vrijkomend)
Sheet piles temporary	Stalen damwand tijdelijk
Anchorage mortar	Groutanker
Work with work: sand	Werk met werk maken: zand (wegenbouw)
Steel pile small	Stalen buis klein
Rebar	Betonstaal
Concrete mortar C35/C45 CEMIII	Betonmortel C35/C45 CEMIII
Driving pile (steel)	Heipaal (staal)
Steel sheet piles	Stalen damwand
Steel pile large	Stalen buis groot
Rubble stone	Breuksteen (waterbouw)
Reused rocks	Hergebruikte steen (waterbouw)
Maintenance dredging (TSHD type)	Onderhoudsbaggerwerk (sleephopperzuiger)
Work with work: sand from dredging	Werk met werk maken: zand uit baggerwerk
Electricity grey	Elektriciteit grijs

Figure D.4: Translation of the DuboCalc objects to Dutch

E

Case study results

E.1. Calculation of the amount of diesel needed for the generators for temporary drainage

From an internal report, the amount of diesel needed to generate energy for one drainage system can be determined. An amount of approx. 22.000 liters was found for one drainage system for an one year time period. During the approx. one year development of the short sea quay wall of HHTT, 37 drainage systems were used. This means that 815,000 liters of diesel was consumed. The case study quay wall was 479.94 meters. This results in approx. 362.200 liters of diesel (815,000*(479.94/1080)).

E.2. Determination of the amount of energy needed for ICCP

The amount of energy needed (in kWh) to protect the quay wall against erosion is dependent on the surface area of the quay wall. The length of the quay wall is 479.94 meters and the sheet piles have an averaged depth of 14.70 meters. This results in a surface area of 7055 m^2. From internal PoR rapports, the electric current of the case study quay wall is at maximum equal to 80 mA/m^2. The energy demand for the ICCP consists of two parts: the standby phase and the start phase. The standby phase is the continuous energy demand over the full life cycle of the quay wall. The start phase is the extra energy demand needed to polarise the quay wall (a required action in the ICCP). In the PoR, approximately three months are counted for this. To calculate the full energy demand of the quay wall, the sum of the standby demand for 100 years and the 3 months additional demand for the start phase should be taken. From the internal rapport, for the standby demand a value of 2.64 kWh/m^2 for a year is found and for the start phase a value of 0.7 kWh/m^2 for 3 months is found. Multiplying this with the surface of the case study and taking the sum, will result in an energy demand of 1.867.490 kWh for 100 years.

E.3. Results of case study using DuboCalc

Action	Dubocalc object	Input	Unit	CO2-eq 479,94 m in kg	CO2-eq 100 m in l	Percentage [%]
Soil excavation	Ground per axle	29.898	m3	267.109	55.655	2,9
Sand backfill	Land sand per axle (released)	9.941	m3	51.429	10.716	0,6
Temporarily sheet piles	Temporarily sheet piles	615	ton	186.188	38.794	2,0
Drainage	Diesel	362.177	l	1.553.724	323.733	17,1
Grout	Grout anchorage	196	m3	92.291	19.230	1,0
Concrete mortar	Concrete mortar C35/C45 CEMIII	4.648	ton	1.220.051	254.209	13,4
Rebar	Rebar	749	m3	845.118	176.088	9,3
Sheet piles	Steel sheet piles	512	ton	603.750	125.797	6,6
Steel piles	Pile (steel)	1.595	ton	1.528.139	318.402	16,8
BBS protection	Total			337.487	70.319	3,7
	Rubble stone (Released) (1 km)	11.720	ton	32.953	6.866	
	Reused rocks (1 km)	35.768	ton	210.814	43.925	
	Rubble stone (15 km)	1.600	ton	93.720	19.527	
Dredging	MDO	227	ton	849.731	177.049	9,3
ICCP	Electricity grey	1.867.490	kWh	1.574.649	328.093	17,3
Total				**9.109.667**	**1.898.085**	**100,0**
Initial value				**9.109.667**	**1.898.085**	

Figure E.1: Results of the case study using DuboCalc

F

Intervention measures

F.1. Technical Readiness Level

Category	Explanation
TRL 1	Basic principles are observed and reported
TRL 2	Technology of concept and/of application are formulated
TRL 3	Proof of concept determined
TRL 4	Laboratory research of prototype components or processes
TRL 5	Laboratory research of the integrated system
TRL 6	Prototype of innovation is verified
TRL 7	Innovation is demonstrated in a integral pilot
TRL 8	Innovation is adapted in commercial design
TRL 9	Innovation ready for implementation on a large scale

Table F.1: An overview of the Technology Readiness Level and its explanation.

F.2. Design change

Standard quay wall				**100m**		**CO2 [kton]**
Volume 1	4,83	Desity rebar/concrete	158	Mass rebar [ton]	137,04	154,63
Volume 2	3,8493	Mass rebar [kg]	1370,42	Volume concrete	850,36	223,20
Volume Capping Beam	8,6793	Volume rebar	0,18			
		Volume concrete	8,50	Total		377,82
Shortend capping beam alternative				**100m**		**CO2 [kton]**
Volume 1 [m3]	4,83	Desity rebar/concrete	158	Mass rebar [ton]	76,26	86,05
Volume 2 [m3]	0	Mass rebar [kg]	762,63	Volume concrete [m2]	473,22	124,21
Volume Capping Beam [m3]	4,83	Volume rebar [m3]	0,10	Fender surface [m2]	264,60	-11,77
		Volume concrete [m3]	4,73	Coating surface [m2]	470,00	534,81
		Volume wooden fender [m3]	0,63	Total		**733,30**
				Total change	Increase	[+] 355,47

Figure F.1: Results of the capping beam calculations

F.3. Possible reduction scenario: Steel production

Action	Dubocalc object	Input	Unit	CO2-eq 479,94 m in kg	CO2-eq 100 m in kg	Percentage [%]
Soil excavation	Ground per axle	29.898	m3	267.109	55.655	3,8
Sand backfill	Land sand per axle (released)	9.941	m3	51.429	10.716	0,7
Temporarily sheet piles	Temporarily sheet piles	615	ton	186.188	38.794	2,7
Drainage	Diesel	362.177	l	1.553.724	323.733	22,2
Grout	Grout anchorage	196	m3	92.291	19.230	1,3
Concrete mortar	Concrete mortar C35/C45 CEMIII	4.648	ton	1.220.051	254.209	17,5
Rebar	Rebar	749	m3	272.214	56.718	3,9
Sheet piles	Steel sheet piles	512	ton	207.939	43.326	3,0
Steel piles	Pile (steel)	1.595	ton	370.724	77.244	5,3
BBS protection	Total			337.487	70.319	4,8
	Rubble stone (Released) (1 km)	11.720	ton	32.953	6.866	
	Reused rocks (1 km)	35.768	ton	210.814	43.925	
	Rubble stone (15 km)	1.600	ton	93.720	19.527	
Dredging	MDO	227	ton	849.731	177.049	12,2
ICCP	Electricity grey	1.867.490	kWh	1.574.649	328.093	22,5
Total				**6.983.537**	**1.455.085**	**24,2**
Inital value				**9.214.741**	**1.919.978**	

Steel sheet piles in ton	Quantity	CO2 per unit	CO2 per ton	Fee	Mass (ton)
Steel GWW (averaged)	1,000	163,44	163,44		512,00
Engine-generator hydraulic 200-500 kW	0,421	197,04	82,97		
Dragline excavator	0,376	79,75	29,98		
Pile driver 500-800 kN	0,421	106,44	44,82		
Transport steel	1,000	0,27	0,27		
Hydraulic pile driver 50 - 200 kNm	0,421	85,81	36,14		
Crane hydraulic	0,421	79,75	33,58		
Pile driver electric (average)	0,376	0,67	0,25		
Total			**391,45**	**1,04**	
Default distance	1,00				
Failure	0,00	**Total emission**	**207.939,25**		**Deviation [%]**
Initial value			603.750,20		0

Rebar in ton	Quantity	CO2 per unit	CO2 per ton	Fee	Mass (ton)
Rebar (averaged)	1,000	163,44	163,44		749,00
Crane hydraulic	0,370	79,75	29,51		
Excavator hydraulic	0,670	52,59	35,24		
Transport steel	1,000	0,27	0,27		
Jackhammer hydraulic 600-1900 kg	0,670	165,00	110,55		
Total			**342,86**	**1,06**	
Default distance	1,00				
Failure	0,02	**Total emission**	**272.214,03**		**Deviation [%]**
Initial value			845.118,38		3

Steel piles in ton	**Quantity**	**CO2 per unit**	**CO2 per ton**	**Fee**	**Mass (ton)**
Steel GWW (averaged)	1,000	163,44	163,44		1.595,00
Dragline excavator	0,303	79,75	24,16		
Hydraulic pile driver (averaged)	0,303	0,67	0,20		
Transport steel	1,000	0,27	0,27		
Excavator hydraulic	0,625	52,59	32,87		
Jackhammer hydraulic	0,625	0,67	0,42		
Total			**221,36**	**1,05**	
Default distance	1,00				
Failure	0,00	**Total emission**	**370.723,62**		**Deviation [%]**
Initial value			1.528.138,99		6

F.4. Possible reduction scenario: dredging fuel change

Action	Dubocalc object	Input	Unit	CO2-eq 479,94 m in kg	CO2-eq 100 m in kg	Percentage [%]
Soil excavation	Ground per axle	29.898	m3	267.109	55.655	3,2
Sand backfill	Land sand per axle (released)	9.941	m3	51.429	10.716	0,6
Temporarily sheet piles	Temporarily sheet piles	615	ton	186.188	38.794	2,2
Drainage	Diesel	362.177	l	1.553.724	323.733	18,3
Grout	Grout anchorage	196	m3	92.291	19.230	1,1
Concrete mortar	Concrete mortar C35/C45 CEMIII	4.648	ton	1.220.051	254.209	14,4
Rebar	Rebar	749	m3	845.118	176.088	10,0
Sheet piles	Steel sheet piles	512	ton	603.750	125.797	7,1
Steel piles	Pile (steel)	1.595	ton	1.528.139	318.402	18,0
BBS protection	Total			337.487	70.319	4,0
	Rubble stone (Released) (1 km)	11.720	ton	32.953	6.866	
	Reused rocks (1 km)	35.768	ton	210.814	43.925	
	Rubble stone (15 km)	1.600	ton	93.720	19.527	
Dredging	HVO	216	ton	211.893	44.150	2,5
ICCP	Electricity grey	1.867.490	kWh	1.574.649	328.093	18,6
Total				**8.471.829**	**1.765.185**	**8,1**
Initial value				**9.214.741**	**1.919.978**	

Action	Dubocalc object	Input	Unit	CO2-eq 479,94 m in kg	CO2-eq 100 m in kg	Percentage [%]
Soil excavation	Ground per axle	29.898	m3	267.109	55.655	3,2
Sand backfill	Land sand per axle (released)	9.941	m3	51.429	10.716	0,6
Temporarily sheet piles	Temporarily sheet piles	615	ton	186.188	38.794	2,2
Drainage	Diesel	362.177	l	1.553.724	323.733	18,3
Grout	Grout anchorage	196	m3	92.291	19.230	1,1
Concrete mortar	Concrete mortar C35/C45 CEMIII	4.648	ton	1.220.051	254.209	14,4
Rebar	Rebar	749	m3	845.118	176.088	10,0
Sheet piles	Steel sheet piles	512	ton	603.750	125.797	7,1
Steel piles	Pile (steel)	1.595	ton	1.528.139	318.402	18,0
BBS protection	Total			337.487	70.319	4,0
	Rubble stone (Released) (1 km)	11.720	ton	32.953	6.866	
	Reused rocks (1 km)	35.768	ton	210.814	43.925	
	Rubble stone (15 km)	1.600	ton	93.720	19.527	
Dredging	LNG	194	ton	774.542	161.383	9,1
ICCP	Electricity grey	1.867.490	kWh	1.574.649	328.093	18,6
Total				**9.034.478**	**1.882.418**	**2,0**
Initial value				**9.214.741**	**1.919.978**	

Action	Dubocalc object	Input	Unit	CO2-eq 479,94 m in kg	CO2-eq 100 m in kg	Percentage [%]
Soil excavation	Ground per axle	29.898	m3	267.109	55.655	3,2
Sand backfill	Land sand per axle (released)	9.941	m3	51.429	10.716	0,6
Temporarily sheet piles	Temporarily sheet piles	615	ton	186.188	38.794	2,2
Drainage	Diesel	362.177	l	1.553.724	323.733	18,3
Grout	Grout anchorage	196	m3	92.291	19.230	1,1
Concrete mortar	Concrete mortar C35/C45 CEMIII	4.648	ton	1.220.051	254.209	14,4
Rebar	Rebar	749	m3	845.118	176.088	10,0
Sheet piles	Steel sheet piles	512	ton	603.750	125.797	7,1
Steel piles	Pile (steel)	1.595	ton	1.528.139	318.402	18,0
BBS protection	Total			337.487	70.319	4,0
	Rubble stone (Released) (1 km)	11.720	ton	32.953	6.866	
	Reused rocks (1 km)	35.768	ton	210.814	43.925	
	Rubble stone (15 km)	1.600	ton	93.720	19.527	
Dredging	Hydrogen (50%)	79	ton	285.111	59.406	3,4
ICCP	Electricity grey	1.867.490	kWh	1.574.649	328.093	18,6
Total				**8.545.047**	**1.780.441**	**7,3**
Initial value				**9.214.741**	**1.919.978**	

Action	Dubocalc object	Input	Unit	CO2-eq 479,94 m in kg	CO2-eq 100 m in kg	Percentage [%]
Soil excavation	Ground per axle	29.898	m3	267.109	55.655	3,2
Sand backfill	Land sand per axle (released)	9.941	m3	51.429	10.716	0,6
Temporarily sheet piles	Temporarily sheet piles	615	ton	186.188	38.794	2,2
Drainage	Diesel	362.177	l	1.553.724	323.733	18,3
Grout	Grout anchorage	196	m3	92.291	19.230	1,1
Concrete mortar	Concrete mortar C35/C45 CEMIII	4.648	ton	1.220.051	254.209	14,4
Rebar	Rebar	749	m3	845.118	176.088	10,0
Sheet piles	Steel sheet piles	512	ton	603.750	125.797	7,1
Steel piles	Pile (steel)	1.595	ton	1.528.139	318.402	18,0
BBS protection	Total			337.487	70.319	4,0
	Rubble stone (Released) (1 km)	11.720	ton	32.953	6.866	
	Reused rocks (1 km)	35.768	ton	210.814	43.925	
	Rubble stone (15 km)	1.600	ton	93.720	19.527	
Dredging	Hydrogen (100%)	79	ton	0	0	0,0
ICCP	Electricity grey	1.867.490	kWh	1.574.649	328.093	18,6
Total				**8.259.936**	**1.721.035**	**10,4**
Initial value				**9.214.741**	**1.919.978**	

F.5. Possible reduction scenario: BEVs trucks

Action	Dubocalc object	Input	Unit	CO2-eq 479,94 m in kg	CO2-eq 100 m in kg	Percentage [%]
Soil excavation	Ground per axle	29.898	m3	108.949	22.701	1,2
Sand backfill	Land sand per axle (released)	9.941	m3	41.970	8.745	0,5
Temporarily sheet piles	Temporarily sheet piles	615	ton	182.083	37.939	2,0
Drainage	Diesel	362.177	l	1.553.739	323.736	17,4
Grout	Grout anchorage	196	m3	89.096	18.564	1,0
Concrete mortar	Concrete mortar C35/C45 CEMIII	4.648	ton	1.107.934	230.848	12,4
Rebar	Rebar	749	m3	874.957	182.305	9,8
Sheet piles	Steel sheet piles	512	ton	603.308	125.705	6,8
Steel piles	Pile (steel)	1.595	ton	1.617.229	336.965	18,1
BBS protection	Total			333.729	69.536	3,7
	Rubble stone (Released) (1 km)	11.720	ton	30.550	6.365	
	Reused rocks (1 km)	35.768	ton	203.580	42.418	
	Rubble stone (15 km)	1.600	ton	99.599	20.752	
Dredging	MDO	227	ton	849.731	177.049	9,5
ICCP	Electricity grey	1.867.490	kWh	1.574.649	328.093	17,6
Total				**8.937.373**	**1.862.186**	**3,0**
Initial value				**9.214.741**	**1.919.978**	

Steel sheet piles in ton	Quantity	CO2 per unit	CO2 per ton	Fee	Mass (ton)
Steel GWW (averaged)	1,000	908,00	908,00		512,00
Engine-generator hydraulic 200-500 kW	0,421	197,04	82,97		
Dragline excavator	0,376	79,75	29,98		
Pile driver 500-800 kN	0,421	106,44	44,82		
Transport steel	1,000	0,00	0,00	##	
Hydraulic pile driver 50 - 200 kNm	0,421	85,81	36,14		
Crane hydraulic	0,421	79,75	33,58		
Pile driver electric (average)	0,376	0,67	0,25		
Total			**1.135,75**	**##**	
Default distance	1,00				
Failure	0,00	**Total emission**	**603.307,94**		**Deviation [%]**
Initial value			603.750,20		0

Rebar in ton	Quantity	CO2 per unit	CO2 per ton	Fee	Mass (ton)
Rebar (averaged)	1,000	908,00	908,00		749,00
Crane hydraulic	0,370	79,75	29,51		
Excavator hydraulic	0,670	52,59	35,24		
Transport steel	1,000	0,00	0,00	##	
Jackhammer hydraulic 600-1900 kg	0,670	165,00	110,55		
Total			**1.102,04**	**##**	
Default distance	1,00				
Failure	0,02	**Total emission**	**874.956,88**		**Deviation [%]**
Initial value			845.118,38		3

Steel piles (heipaal) in ton	Quantity	CO2 per unit	CO2 per ton	Fee	Mass (ton)
Steel GWW (averaged)	1,000	908,00	908,00		1.595,00
Dragline excavator	0,303	79,75	24,16		
Hydraulic pile driver (averaged)	0,303	0,67	0,20		
Transport steel	1,000	0,00	0,00	##	
Excavator hydraulic	0,625	52,59	32,87		
Jackhammer hydraulic	0,625	0,67	0,42		
Total			**965,65**	**##**	
Default distance	1,00				
Failure	0,00	**Total emission**	**1.617.229,11**		**Deviation [%]**
Initial value			1.528.138,99		6

Temporary sheet piles in ton	Quantity	CO2 per unit	CO2 per ton	Fee	Mass (ton)
Engine-generator hydraulic 200-500 kW	0,421	197,04	82,97		615,00
Dragline excavator	0,376	79,75	29,98		
Pile driver electric (average)	0,376	0,67	0,25		
Hydraulic pile driver 500 - 800 kNm	0,421	106,44	44,82		
Pile driver 50-200 kN	0,421	85,81	36,14		
Crane hydraulic	0,421	79,75	33,58		
Transport steel	1,000	0,00	0,00	##	
Total			**227,75**	**##**	
Default distance	1,00				
Failure	0,00	**Total emission**	**182.082,50**		**Deviation [%]**
Initial value			186.187,85		2

Ground per axle	Quantity	CO2 per unit	CO2 per m3	Fee	Volume (m3)
Soil	1,625	0,00	0,00		29.898,00
Excavator hydraulic	0,014	52,59	0,75		
Transport bulk (road)	1,625	0,00	0,00	##	
Bulldozer 12-35 t dry/wet	0,014	64,79	0,93		
Total			**1,72**	**##**	
Default distance	75,00				
Failure	0,05	**Total emission**	**108.948,96**		**Deviation [%]**
Initial value			267.108,58		145

Land sand (Released)	Quantity	CO2 per unit	CO2 per m3	Fee	Volume (m3)
Land Sand	1,700	2,72	0,00		9.941,00
Road roller (avg.)	0,010	49,50	0,49		
Wheel loader	0,010	43,49	0,43		
Excavator hydraulic (avg.)	0,009	52,59	0,46		
Transport bulk (road)	1,700	0,00	0,00	##	
Total			**2,48**	**##**	
Default distance	75,00				
Failure	0,05	**Total emission**	**41.969,80**		**Deviation [%]**
Initial value			51.429,40		23

Concrete mortar C35/45 (CEMIII)	Quantity	CO2 per unit	CO2 per m3	Fee	Volume (m3)
Concrete mortar C35/45 (CEMIII)	2,440	58,04	141,62		4.648,31
Excavator hydraulic (avg.)	0,040	52,59	2,10		
Excavator hydraulic (avg.)	0,060	52,59	3,16		
Concrete pump incl. vehicle	0,010	6,17	0,06		
Jackhammer hydraulic 600 - 1900 kg	0,040	165,00	6,60		
Excavator hydraulic (avg.)	0,400	52,59	21,04		
Concrete vibrating needle	0,400	0,10	0,04		
Transport bulk (road)	2,440	0,00	0,00	##	
Total			**183,35**	**##**	
Default distance	20,00				
Failure	0,05	**Total emission**	**1.107.934,16**		**Deviation [%]**
Initial value			1.220.051,47		10

Grout	Quantity	CO2 per unit	CO2 per m3	Fee	Volume (m3)
Grout	1,600	211,43	338,29		196,30
Compr. diesel 3.5-10.0 m3/min	0,040	42,34	1,69		
Concrete pump incl. vehicle	0,040	6,17	0,25		
Excavator hydraulic (avg.)	0,040	52,59	2,10		
Transport bulk (road)	1,600	0,00	0,00	##	
Total			**349,13**	**##**	
Default distance	20,00				
Failure	0,02	**Total emission**	**89.095,54**		**Deviation [%]**
Initial value			92.291,23		4

Rubble stone	Quantity	CO2 per unit	CO2 per ton	Fee	Mass (ton)
Rubble stone (avg)	1,000	39,87	39,87		1.600,00
Work boat 360-590 kW	0,004	139,28	0,50		
Transport bulk (water)	1,000	0,00	0,00	##	
Ponton (avg)	0,004	0,00	0,00		
Excavator (avg)	0,004	46,06	0,16		
Excavator (avg)	0,004	46,06	0,16		
Ponton (avg)	0,004	0,00	0,00		
Total			**47,88**	**##**	
Default distance	15,00				
Failure	0,02	**Total emission**	**99.599,05**		**Deviation [%]**
Initial value			93.719,78		6

Reused rocks	Quantity	CO2 per unit	CO2 per ton	Fee	Mass (ton)
Rubble stone (avg)	1,000	39,87	0,00		35.767,53
Work boat 360-590 kW	0,007	139,28	0,97		
Transport bulk (water)	1,000	0,00	0,00	##	
Ponton (avg)	0,007	0,00	0,00		
Excavator (avg)	0,007	46,06	0,32		
Excavator (avg)	0,007	46,06	0,32		
Ponton (avg)	0,007	0,00	0,00		
Total			**4,38**	**##**	
Default distance	100,00				
Failure	0,02	**Total emission**	**203.580,29**		**Deviation [%]**
Initial value			210.814,16		4

Rubble stone (released)	Quantity	CO2 per unit	CO2 per ton	Fee	Mass (ton)
Rubble stone (avg)	1,000	39,87	0,00		11.720,31
Work boat 360-590 kW	0,004	139,28	0,50		
Transport bulk (water)	1,000	0,00	0,00	##	
Ponton (avg)	0,004	0,00	0,00		
Excavator (avg)	0,004	46,06	0,16		
Excavator (avg)	0,004	46,06	0,16		
Ponton (avg)	0,004	0,00	0,00		
Total			**2,07**	**##**	
Default distance	15,00				
Failure	0,02	**Total emission**	**30.550,06**		**Deviation [%]**
Initial value			32.953,11		8

F.6. Possible reduction scenario: Concrete production

Action	Dubocalc object	Input	Unit	CO2-eq 479,94 m in kg	CO2-eq 100 m in kg	Percentage [%]
Soil excavation	Ground per axle	29.898	m3	279.324	58.200	3,3
Sand backfill	Land sand per axle (released)	9.941	m3	50.008	10.420	0,6
Temporarily sheet piles	Temporarily sheet piles	615	ton	182.296	37.983	2,2
Drainage	Diesel	362.177	l	1.553.739	323.736	18,5
Grout	Grout anchorage	196	m3	89.207	18.587	1,1
Concrete mortar	Concrete mortar C35/C45 CEMIII	4.648	ton	381.708	79.532	4,5
Rebar	Rebar	749	m3	875.173	182.350	10,4
Sheet piles	Steel sheet piles	512	ton	603.449	125.734	7,2
Steel piles	Pile (steel)	1.595	ton	1.617.675	337.058	19,2
BBS protection	Total			349.053	72.728	4,2
	Rubble stone (Released) (1 km)	11.720	ton	33.908	7.065	
	Reused rocks (1 km)	35.768	ton	215.327	44.865	
	Rubble stone (15 km)	1.600	ton	99.818	20.798	
Dredging	MDO	227	ton	849.731	177.049	10,1
ICCP	Electricity grey	1.867.490	kWh	1.574.649	328.093	18,7
Total				**8.406.011**	**1.751.471**	**8,8**
Initial value				**9.214.741**	**1.919.978**	

Concrete mortar C35/45 (CEMIII)	**Quantity**	**CO2 per unit**	**CO2 per m3**	**Fee**	**Volume (m3)**
Concrete mortar C35/45 (CEMIII)	2,440	5,80	14,16	##	4.648,31
Excavator hydraulic (avg.)	0,040	52,59	2,10		
Excavator hydraulic (avg.)	0,060	52,59	3,16		
Concrete pump incl. vehicle	0,010	6,17	0,06		
Jackhammer hydraulic 600 - 1900 kg	0,040	165,00	6,60		
Excavator hydraulic (avg.)	0,400	52,59	21,04		
Concrete vibrating needle	0,400	0,10	0,04		
Transport bulk (road)	2,440	0,27	0,65		
Total			**63,17**	**##**	
Default distance	20,00				
Failure	0,05	**Total emission**	**381.707,55**		**Deviation [%]**
Initial value			1.220.051,47		220

F.7. Possible reduction scenario: construction machinery

Action	Dubocalc object	Input	Unit	CO2-eq 479,94 m in kg	CO2-eq 100 m in kg	Percentage [%]
Soil excavation	Ground per axle	29.898	m3	181.270	37.769	2,2
Sand backfill	Land sand per axle (released)	9.941	m3	28.205	5.877	0,3
Temporarily sheet piles	Temporarily sheet piles	615	ton	18.421	3.838	0,2
Drainage	Diesel	362.177	l	1.553.739	323.736	18,9
Grout	Grout anchorage	196	m3	88.269	18.392	1,1
Concrete mortar	Concrete mortar C35/C45 CEMIII	4.648	ton	1.002.027	208.782	12,2
Rebar	Rebar	749	m3	749.495	156.164	9,1
Sheet piles	Steel sheet piles	512	ton	494.569	103.048	6,0
Steel piles	Pile (steel)	1.595	ton	1.527.569	318.283	18,6
BBS protection	Total			136.544	28.450	1,7
	Rubble stone (Released) (1 km)	11.720	ton	6.413	1.336	
	Reused rocks (1 km)	35.768	ton	32.105	6.689	
	Rubble stone (15 km)	1.600	ton	98.026	20.425	
Dredging	MDO	227	ton	849.731	177.049	10,4
ICCP	Electricity grey	1.867.490	kWh	1.574.649	328.093	19,2
Total				**8.204.489**	**1.709.482**	**11,0**
Initial value				**9.214.741**	**1.919.978**	

Steel sheet piles in ton	Quantity	CO2 per unit	CO2 per ton	Fee	Mass (ton)
Steel GWW (averaged)	1,000	908,00	908,00		512,00
Engine-generator hydraulic 200-500 kW	0,421	19,70	8,30		
Dragline excavator	0,376	7,97	3,00		
Pile driver 500-800 kN	0,421	10,64	4,48		
Transport steel	1,000	0,27	0,27		
Hydraulic pile driver 50 - 200 kNm	0,421	8,58	3,61		
Crane hydraulic	0,421	7,97	3,36		
Pile driver electric (average)	0,376	0,07	0,03		
Total			**931,04**	**##**	
Default distance	1,00				
Failure	0,00	**Total emission**	**494.568,93**		**Deviation [%]**
Initial value			603.750,20		22

Rebar in ton	Quantity	CO2 per unit	CO2 per ton	Fee	Mass (ton)
Rebar (averaged)	1,000	908,00	908,00		749,00
Crane hydraulic	0,370	7,97	2,95		
Excavator hydraulic	0,670	5,26	3,52		
Transport steel	1,000	0,27	0,27		
Jackhammer hydraulic 600-1900 kg	0,670	16,50	11,05		
Total			**944,02**	**##**	
Default distance	1,00				
Failure	0,02	**Total emission**	**749.495,33**		**Deviation [%]**
Initial value			845.118,38		13

Steel piles (heipaal) in ton	Quantity	CO2 per unit	CO2 per ton	Fee	Mass (ton)
Steel GWW (averaged)	1,000	908,00	908,00		1.595,00
Dragline excavator	0,303	1,66	0,50		
Hydraulic pile driver (averaged)	0,303	0,07	0,02		
Transport steel	1,000	0,27	0,27		
Excavator hydraulic	0,625	5,26	3,29		
Jackhammer hydraulic	0,625	0,07	0,04		
Total			**912,12**	**##**	
Default distance	1,00				
Failure	0,00	**Total emission**	**1.527.568,91**		**Deviation [%]**
Initial value			1.528.138,99		0

Temporary sheet piles in ton	Quantity	CO2 per unit	CO2 per ton	Fee	Mass (ton)
Engine-generator hydraulic 200-500 kW	0,421	19,70	8,30		615,00
Dragline excavator	0,376	7,97	3,00		
Pile driver electric (average)	0,376	0,07	0,03		
Hydraulic pile driver 500 - 800 kNm	0,421	10,64	4,48		
Pile driver 50-200 kN	0,421	8,58	3,61		
Crane hydraulic	0,421	7,97	3,36		
Transport steel	1,000	0,27	0,27		
Total			**23,04**	**##**	
Default distance	1,00				
Failure	0,00	**Total emission**	**18.421,28**		**Deviation [%]**
Initial value			186.187,85		911

Ground per axle	Quantity	CO2 per unit	CO2 per m3	Fee	Volume (m3)
Soil	1,625	0,00	0,00		29.898,00
Excavator hydraulic	0,014	5,26	0,08		
Transport bulk (road)	1,625	0,27	0,43		
Bulldozer 12-35 t dry/wet	0,014	6,48	0,09		
Total			**2,87**	**##**	
Default distance	75,00				
Failure	0,05	**Total emission**	**181.269,91**		**Deviation [%]**
Initial value			267.108,58		47

Land sand (Released)	Quantity	CO2 per unit	CO2 per m3	Fee	Volume (m3)
Land Sand	1,700	2,72	0,00		9.941,00
Road roller (avg.)	0,010	4,95	0,05		
Wheel loader	0,010	4,35	0,04		
Excavator hydraulic (avg.)	0,009	5,26	0,05		
Transport bulk (road)	1,700	0,27	0,45		
Total			**1,67**	**##**	
Default distance	75,00				
Failure	0,05	**Total emission**	**28.205,10**		**Deviation [%]**
Initial value			51.429,40		82

Concrete mortar C35/45 (CEMIII)	Quantity	CO2 per unit	CO2 per m3	Fee	Volume (m3)
Concrete mortar C35/45 (CEMIII)	2,440	58,04	141,62		4.648,31
Excavator hydraulic (avg.)	0,040	5,26	0,21		
Excavator hydraulic (avg.)	0,060	5,26	0,32		
Concrete pump incl. vehicle	0,010	0,62	0,01		
Jackhammer hydraulic 600 - 1900 kg	0,040	16,50	0,66		
Excavator hydraulic (avg.)	0,400	5,26	2,10		
Concrete vibrating needle	0,400	0,01	0,00		
Transport bulk (road)	2,440	0,27	0,65		
Total			**165,82**	**##**	
Default distance	20,00				
Failure	0,05	**Total emission**	**1.002.027,34**		**Deviation [%]**
Initial value			1.220.051,47		22

Grout	Quantity	CO2 per unit	CO2 per m3	Fee	Volume (m3)
Grout	1,600	211,43	338,29		196,30
Compr. diesel 3.5-10.0 m3/min	0,040	4,23	0,17		
Concrete pump incl. vehicle	0,040	0,62	0,02		
Excavator hydraulic (avg.)	0,040	5,26	0,21		
Transport bulk (road)	1,600	0,27	0,43		
Total			**345,89**	**##**	
Default distance	20,00				
Failure	0,02	**Total emission**	**88.268,83**		**Deviation [%]**
Initial value			92.291,23		5

Rubble stone	Quantity	CO2 per unit	CO2 per ton	Fee	Mass (ton)
Rubble stone (avg)	1,000	39,87	39,87		1.600,00
Work boat 360-590 kW	0,004	13,93	0,05		
Transport bulk (water)	1,000	0,05	0,05		
Ponton (avg)	0,004	0,00	0,00		
Excavator (avg)	0,004	4,61	0,02		
Excavator (avg)	0,004	4,61	0,02		
Ponton (avg)	0,004	0,00	0,00		
Total			**47,13**	**##**	
Default distance	15,00				
Failure	0,02	**Total emission**	**98.026,39**		**Deviation [%]**
Initial value			93.719,78		4

Reused rocks	Quantity	CO2 per unit	CO2 per ton	Fee	Mass (ton)
Rubble stone (avg)	1,000	39,87	0,00		35.767,53
Work boat 360-590 kW	0,007	13,93	0,10		
Transport bulk (water)	1,000	0,05	0,05		
Ponton (avg)	0,007	0,00	0,00		
Excavator (avg)	0,007	4,61	0,03		
Excavator (avg)	0,007	4,61	0,03		
Ponton (avg)	0,007	0,00	0,00		
Total			**0,69**	**##**	
Default distance	100,00				
Failure	0,02	**Total emission**	**32.104,67**		**Deviation [%]**
Initial value			210.814,16		557

Rubble stone (released)	Quantity	CO2 per unit	CO2 per ton	Fee	Mass (ton)
Rubble stone (avg)	1,000	39,87	0,00		11.720,31
Work boat 360-590 kW	0,004	13,93	0,05		
Transport bulk (water)	1,000	0,05	0,05		
Ponton (avg)	0,004	0,00	0,00		
Excavator (avg)	0,004	4,61	0,02		
Excavator (avg)	0,004	4,61	0,02		
Ponton (avg)	0,004	0,00	0,00		
Total			**0,44**	**##**	
Default distance	15,00				
Failure	0,02	**Total emission**	**6.412,95**		**Deviation [%]**
Initial value			32.953,11		414

F.8. Possible reduction scenario: Electricity generation

Action	Dubocalc object	Input	Unit	CO2-eq 479,94 m in kg	CO2-eq 100 m in kg	Percentage [%]
Soil excavation	Ground per axle	29.898	m3	279.324	58.200	3,6
Sand backfill	Land sand per axle (released)	9.941	m3	50.008	10.420	0,6
Temporarily sheet piles	Temporarily sheet piles	615	ton	182.296	37.983	2,3
Drainage	Diesel	362.177	l	1.553.739	323.736	19,8
Grout	Grout anchorage	196	m3	89.207	18.587	1,1
Concrete mortar	Concrete mortar C35/C45 CEMIII	4.648	ton	1.190.438	248.039	15,2
Rebar	Rebar	749	m3	875.173	182.350	11,1
Sheet piles	Steel sheet piles	512	ton	603.449	125.734	7,7
Steel piles	Pile (steel)	1.595	ton	1.617.675	337.058	20,6
BBS protection	Total			349.053	72.728	4,4
	Rubble stone (Released) (1 km)	11.720	ton	33.908	7.065	
	Reused rocks (1 km)	35.768	ton	215.327	44.865	
	Rubble stone (15 km)	1.600	ton	99.818	20.798	
Dredging	MDO	227	ton	849.731	177.049	10,8
ICCP	Electricity green	1.867.490	kWh	209.617	43.676	2,7
Total				**7.849.709**	**1.635.561**	**14,8**
Initial value				**9.214.741**	**1.919.978**	

Energy green	Quantity	CO2 per unit	CO2 per kWh	Fee	Energy (kWh)
Energy green	1,000	0,09	0,09		1.867.490,00
Total			**0,09**	**##**	
Default distance					
Failure		**Total emission**	**209.617,03**		**Deviation [%]**
Initial value			209.617,02		0

F.9. Possible reduction scenario: diesel to electricity

Action	Dubocalc object	Input	Unit	CO2-eq 479,94 m in kg	CO2-eq 100 m in kg	Percentage [%]
Soil excavation	Ground per axle	29.898	m3	279.324	58.200	3,0
Sand backfill	Land sand per axle (released)	9.941	m3	50.008	10.420	0,5
Temporarily sheet piles	Temporarily sheet piles	615	ton	182.296	37.983	1,9
Drainage	Grey electricity	2.130.300	kWh	1.796.247	374.265	19,0
Grout	Grout anchorage	196	m3	89.207	18.587	0,9
Concrete mortar	Concrete mortar C35/C45 CEMIII	4.648	ton	1.190.438	248.039	12,6
Rebar	Rebar	749	m3	875.173	182.350	9,3
Sheet piles	Steel sheet piles	512	ton	603.449	125.734	6,4
Steel piles	Pile (steel)	1.595	ton	1.617.675	337.058	17,1
BBS protection	Total			349.053	72.728	3,7
	Rubble stone (Released) (1 km)	11.720	ton	33.908	7.065	
	Reused rocks (1 km)	35.768	ton	215.327	44.865	
	Rubble stone (15 km)	1.600	ton	99.818	20.798	
Dredging	MDO	227	ton	849.731	177.049	9,0
ICCP	Electricity grey	1.867.490	kWh	1.574.649	328.093	16,7
Total				**9.457.249**	**1.970.507**	**2,6**
Initial value				**9.214.741**	**1.919.978**	

Energy grey (GENERATOR)	Quantity	CO2 per unit	CO2 per kWh	Fee	Energy (kWh)
Energy grey	1,000	0,65	0,65		2130300
Total			**0,65**	**##**	
Default distance	-				
Failure	-	**Total emission**	**1.796.247,40**		**Deviation [%]**
Initial value					

Action	Dubocalc object	Input	Unit	CO2-eq 479,94 m in kg	CO2-eq 100 m in kg	Percentage [%]
Soil excavation	Ground per axle	29.898	m3	279.324	58.200	3,5
Sand backfill	Land sand per axle (released)	9.941	m3	50.008	10.420	0,6
Temporarily sheet piles	Temporarily sheet piles	615	ton	182.296	37.983	2,3
Drainage	Grey electricity	2.130.300	kWh	239.116	49.822	3,0
Grout	Grout anchorage	196	m3	89.207	18.587	1,1
Concrete mortar	Concrete mortar C35/C45 CEMIII	4.648	ton	1.190.438	248.039	15,1
Rebar	Rebar	749	m3	875.173	182.350	11,1
Sheet piles	Steel sheet piles	512	ton	603.449	125.734	7,6
Steel piles	Pile (steel)	1.595	ton	1.617.675	337.058	20,5
BBS protection	Total			349.053	72.728	4,4
	Rubble stone (Released) (1 km)	11.720	ton	33.908	7.065	
	Reused rocks (1 km)	35.768	ton	215.327	44.865	
	Rubble stone (15 km)	1.600	ton	99.818	20.798	
Dredging	MDO	227	ton	849.731	177.049	10,8
ICCP	Electricity grey	1.867.490	kWh	1.574.649	328.093	19,9
Total				**7.900.118**	**1.646.064**	**14,3**
Initial value				**9.214.741**	**1.919.978**	

Energy green	Quantity	CO2 per unit	CO2 per kWh	Fee	Energy (kWh)
Energy green	1,000	0,09	0,09		2.130.300,00
Total			**0,09**	**##**	
Default distance					
Failure		**Total emission**	**239.116,22**		**Deviation [%]**
Initial value					

F.10. Results of possible scenarios in time

Possible 2019:

Action	Dubocalc object	Input	Unit	CO2-eq 479,94 m in kg	CO2-eq 100 m in kg	Percentage [%]
Soil excavation	Ground per axle	29.898	m3	267.109	55.655	4,6
Sand backfill	Land sand per axle (released)	9.941	m3	51.429	10.716	0,9
Temporarily sheet piles	Temporarily sheet piles	615	ton	186.188	38.794	3,2
Drainage	Electricity green	2.130.300	kWh	239.116	49.822	4,1
Grout	Grout anchorage	196	m3	92.291	19.230	1,6
Concrete mortar	Concrete mortar C35/C45 CEMIII	4.648	ton	1.220.051	254.209	21,1
Rebar	Rebar	749	m3	845.118	176.088	14,6
Sheet piles	Steel sheet piles	512	ton	603.750	125.797	10,4
Steel piles	Pile (steel)	1.595	ton	1.528.139	318.402	26,4
BBS protection	Total			337.487	70.319	5,8
	Rubble stone (Released) (1 km)	11.720	ton	32.953	6.866	
	Reused rocks (1 km)	35.768	ton	210.814	43.925	
	Rubble stone (15 km)	1.600	ton	93.720	19.527	
Dredging	HVO	216	ton	211.893	44.150	3,7
ICCP	Electricity green	1.867.490	kWh	209.617	43.676	3,6
Total				**5.792.189**	**1.206.857**	**37,1**
Initial value				**9.214.741**	**1.919.978**	

Possible 2025:

Action	Dubocalc object	Input	Unit	CO2-eq 479,94 m in kg	CO2-eq 100 m in kg	Percentage [%]
Soil excavation	Ground per axle	29.898	m3	108.949	22.701	1,9
Sand backfill	Land sand per axle (released)	9.941	m3	41.970	8.745	0,7
Temporarily sheet piles	Temporarily sheet piles	615	ton	182.083	37.939	3,2
Drainage	Electricity green	2.130.300	kWh	239.116	49.822	4,3
Grout	Grout anchorage	196	m3	89.096	18.564	1,6
Concrete mortar	Concrete mortar C35/C45 CEMIII	4.648	ton	1.107.934	230.848	19,7
Rebar	Rebar	749	m3	874.957	182.305	15,6
Sheet piles	Steel sheet piles	512	ton	603.308	125.705	10,7
Steel piles	Pile (steel)	1.595	ton	1.617.229	336.965	28,8
BBS protection	Total			333.729	69.536	5,9
	Rubble stone (Released) (1 km)	11.720	ton	30.550	6.365	
	Reused rocks (1 km)	35.768	ton	203.580	42.418	
	Rubble stone (15 km)	1.600	ton	99.599	20.752	
Dredging	HVO	216	ton	211.893	44.150	3,8
ICCP	Electricity green	1.867.490	kWh	209.617	43.676	3,7
Total				**5.619.881**	**1.170.955**	**39,0**
Initial value				**9.214.741**	**1.919.978**	

Possible 2030:

Action	Dubocalc object	Input	Unit	CO2-eq 479,94 m in kg	CO2-eq 100 m in kg	Percentage [%]
Soil excavation	Ground per axle	29.898	m3	10.895	2.270	0,3
Sand backfill	Land sand per axle (released)	9.941	m3	20.167	4.202	0,5
Temporarily sheet piles	Temporarily sheet piles	615	ton	18.208	3.794	0,5
Drainage	Electricity green	2.130.300	kWh	239.116	49.822	6,3
Grout	Grout anchorage	196	m3	88.158	18.369	2,3
Concrete mortar	Concrete mortar C35/C45 CEMIII	4.648	ton	110.793	23.085	2,9
Rebar	Rebar	749	m3	749.280	156.119	19,7
Sheet piles	Steel sheet piles	512	ton	494.427	103.019	13,0
Steel piles	Pile (steel)	1.595	ton	1.527.123	318.190	40,2
BBS protection	Total			121.221	25.257	3,2
	Rubble stone (Released) (1 km)	11.720	ton	3.055	637	
	Reused rocks (1 km)	35.768	ton	20.358	4.242	
	Rubble stone (15 km)	1.600	ton	97.808	20.379	
Dredging	HVO	216	ton	211.893	44.150	5,6
ICCP	Electricity green	1.867.490	kWh	209.617	43.676	5,5
Total				**3.800.898**	**791.953**	**58,8**
Initial value				**9.214.741**	**1.919.978**	

Possible 2050:

Action	Dubocalc object	Input	Unit	CO2-eq 479,94 m in kg	CO2-eq 100 m in kg	Percentage [%]
Soil excavation	Ground per axle	29.898	m3	10.895	2.270	0,8
Sand backfill	Land sand per axle (released)	9.941	m3	20.167	4.202	1,5
Temporarily sheet piles	Temporarily sheet piles	615	ton	18.208	3.794	1,4
Drainage	Electricity green	2.130.300	kWh	239.116	49.822	17,8
Grout	Grout anchorage	196	m3	88.158	18.369	6,6
Concrete mortar	Concrete mortar C35/C45 CEMIII	4.648	ton	110.793	23.085	8,2
Rebar	Rebar	749	m3	146.321	30.487	10,9
Sheet piles	Steel sheet piles	512	ton	98.917	20.610	7,4
Steel piles	Pile (steel)	1.595	ton	280.171	58.376	20,9
BBS protection	Total			121.221	25.257	9,0
	Rubble stone (Released) (1 km)	11.720	ton	3.055	637	
	Reused rocks (1 km)	35.768	ton	20.358	4.242	
	Rubble stone (15 km)	1.600	ton	97.808	20.379	
Dredging	Hydrogen (100%)	79	ton	0	0	0,0
ICCP	Electricity green	1.867.490	kWh	209.617	43.676	15,6
Total				**1.343.585**	**279.948**	**85,4**
Initial value				**9.214.741**	**1.919.978**	