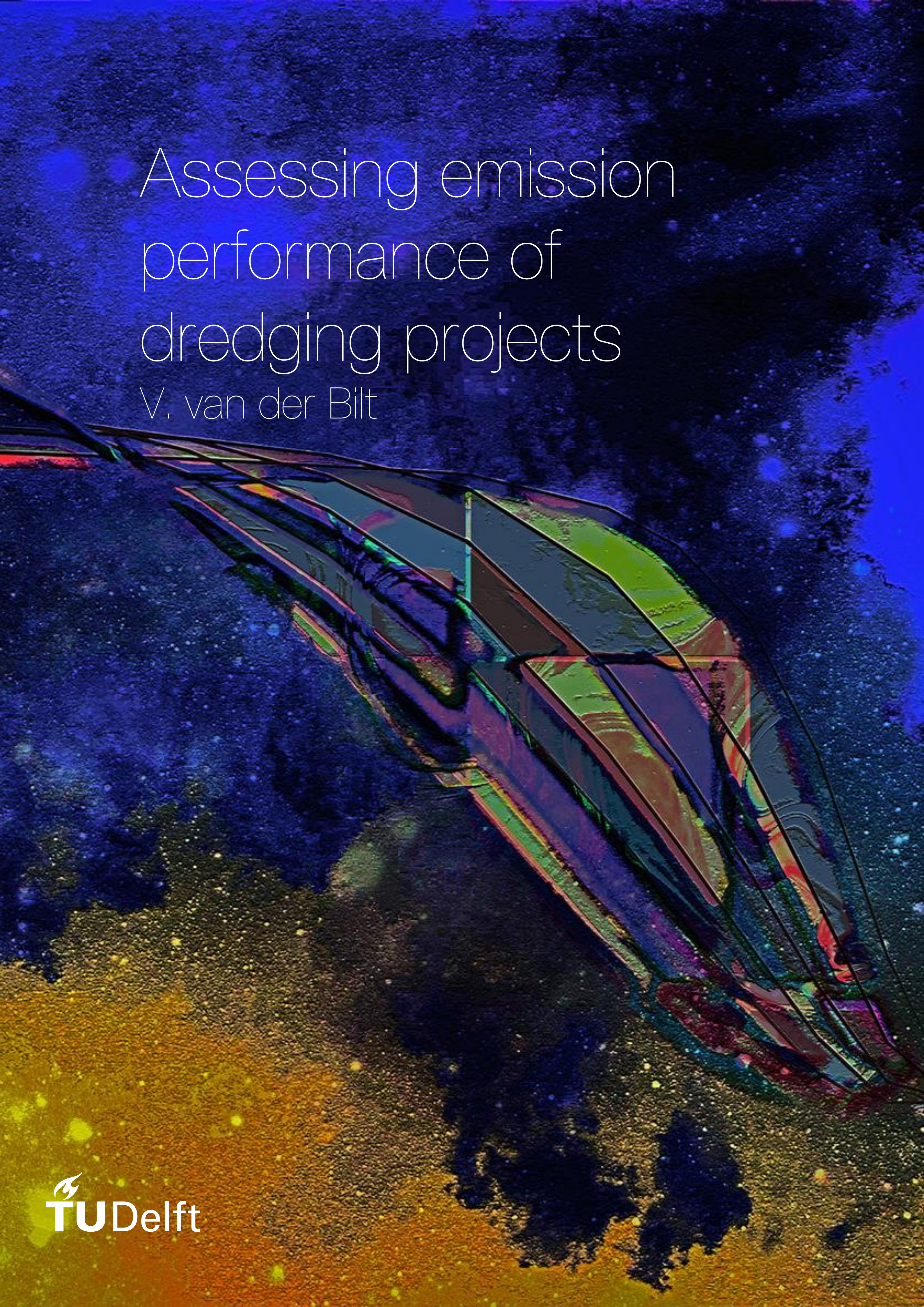

Assessing emission performance of dredging projects

V. van der Bilt

TU Delft

Front cover artwork: Time to Choose by Alisa Singer - www.environmentalgraphiti.org
The artwork was inspired on a graph, from the Fourth National Climate Assessment, US Global Change Research Program. This graph shows possible pathways to reduce global greenhouse gas emissions to limit global mean temperature rise in the post-industrial era to not more than 2°C (3.6°F). The graph demonstrates the critical importance of prompt and aggressive responses in order to avoid the need for more drastic mitigation measures in the future. The black curves reflect the fastest reduction scenarios, resulting in the least need for future negative emissions.

Assessing emission performance of dredging projects

by

Vibeke van der Bilt

to obtain the degree of Master of Science
at the Delft University of Technology,
to be defended publicly on Tuesday July 3, 2019 at 13:00 AM.

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Preface

This research has been conducted as the last part of the program Hydraulic Engineering, at the faculty of Civil Engineering and Geosciences of the Delft University of Technology, to obtain a master's degree.

The research has been performed in collaboration with Van Oord, an international dredging and offshore contractor. The motivation of this research originates from the Dutch Coastline Challenge, a movement of organizations that, on the basis of innovative cooperation, want to achieve a more environmental friendly way of coastline preservation. During my entire research, Van Oord has provided me with enthusiasm, guidance and support. I would like thank Van Oord for giving me this opportunity. Furthermore I would like to take this opportunity to thank everyone else who supported me during the process.

To begin with, I would like to thank my daily supervisor and chair of my committee Mark van Koningsveld for his enthusiasm and dedication to the research. Furthermore I would like to tank my other committee members Myron van Damme and Poonam Taneja, for helping me through the process and providing me with their feedback. Lastly, I would like to thank Joris den Uijl, who helped me finding joy in programming, and also with my struggles with Python when I got stuck.

Vibeke van der Bilt
Rotterdam, June 2019

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Nomenclature

List of abbreviations

AIS	Automatic identification system
ABS	Agent Base Simulation
BHD	Backhoe Dredger
CBS	Centraal Bureau voor de Statistiek *Statistic Netherlands*
CEDA	Central Dredging Association
CO_2	Carbon Dioxide
$CO_2 - eq$	Carbon Dioxide equivalent
CSD	Cutter Suction Dredger
D	Dumping
DES	Discrete Event Simulation
EEDI	Efficiency Design Index
EPA	US Environmental Protection Agency
EUDA	Europe Dredging Association
GHG	Greenhouse gas
GWP	global warming potential
HFO	Heavy Fuel Oil
IMO	International Maritime Organization
LNG	Liquified natural gas
MDO	Marine Diesel Oil
OpenCLSim	Open Complex Logistics Simulation
P	Pumping
RB	Rainbowing
RWS	Rijkswaterstaat
TDD	Test driven development
TSHD	Trailing Suction Hopper Dredger
UNFCCC	United Nation Framework Convention on Climate Change

List of Greek symbols

α	Inlet loss factor	(-)
η	Efficiency	(-)
λ	Resistance factor of straight parts	(-)
ρ_m	Mixture density	(kg/m^3)
ρ_{hopper}	Density of the hopper	(kg/m^3)
ρ_s	Density of the dredged material	(kg/m^3)
ρ_w	Density of the water	(kg/m^3)
ξ_d	Loss factor for bends in discharge pipe	(-)
ξ_s	Loss factor for bends in suction pipe	(-)

List of Latin symbols

A	Distance pump center to waterline	(m)
A_d	Area of the discharge pipe	(m^2)
A_s	Area a the suction pipes	(m^2)
C_F	Conversion factor for a specific fuel type	(kg emission / kg fuel)
C_s	apparent concentration	(-)
C_v	Volume of grains divided by the volume of the mixture	(-)
D_d	Diameter of the discharge pipe	(m)
D_s	Diameter of the suction pipe	(m)
DWT	Maximal carrying capacity of a vessel	(TDS)
$E_{dredging}$	Energy required during dredging event	(kWh)
$E_{sailingfull}$	Energy required during sailing full event	(kWh)
$E_{unloading}$	Energy required during unloading event	(kWh)
$E_{sailingempty}$	Energy required during sailing empty event	(kWh)
f_t	Transport factor	(-)
g	gravitational acceleration	(m/s^2)
H	Distance waterline until discharge outlet	(m)
H_i	Pressure head due to inlet resistance	(mwc)
H_{ksi}	Pressure head due to resistance non-straight parts pipeline	(mwc)
H_{lift}	Pressure head due to resistance lifted height	(mwc)
H_{man}	Manometric head	(mwc)
H_p	Pressure head discharge pipe	(mwc)
H_r	Pressure head due to resistance straight parts pipeline	(mwc)
H_v	Pressure head due to velocities	(mwc)
$h_{penetration}$	Jet penetration depth	(m)
L_s	Length of the suction pipe	(m)
L_d	Length of the discharge pipe	(m)
n_s	Number of suction pipes operating	(-)
n	Porosity	(-)
P	Average power consumption	(kW)
$P_{hydraulic}$	Hydraulic power	(kW)
P_{shaft}	Shaft power	(kW)
$P_{dredging}$	Power required during dredging event	(kW)
$P_{sailingfull}$	Power required during sailing full event	(kW)
$P_{unloading}$	Power required during unloading event	(kW)
$P_{sailingempty}$	Power required during sailing empty event	(kW)
Q_d	the discharge flow	(m/s)
$Q_{g\ jet}$	Production of the jet	(m^3/s)
$Q_{g\ vacuum}$	Production at the available vacuum	(m^3/s)
SFC	Fuel Consumption	(kg / kWh)
$t_{dredging}$	Time duration for dredging event	(sec)
$t_{sailingfull}$	Time duration for sailing full event	(sec)
$t_{unloading}$	Time duration for unloading event	(sec)
$t_{sailingempty}$	Time duration for sailing empty event	(sec)
t_{OV}	the time until overflow	(sec)
T	in situ weight of material (effective load)	(kg)
V_{ref}	Vessel speed	(knots)
V_{hopper}	the volume of the hopper	(m3)
v_{crit}	Critical sediment velocity in discharge pipe	(m/s)
v_d	Sediment velocity in discharge pipe	(m/s)
v_m	Velocity of the mixture	(m/s)
v_s	Sediment velocity in suction pipe	(m/s)
v_{trail}	Trail speed of the hopper	(m/s)
$w_{draghead}$	Width of the draghead	(m)
Z	Extraction depth	(m)

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Abstract

An ongoing trend of increased environmental awareness and a corresponding willingness to combat climate change influences the dredging industry. Policy developments that encourage contractors to work more sustainable and shifting client demands indicate that the amount of emitted CO_2 is becoming an increasingly significant incentive for tender assessment. To increase the probability of winning a tender and make a profit, Van Oord needs to be able to quantify the emitted CO_2 during both the engineering phase and the execution phase.

Due to the high operational costs of dredging vessels the project strategy is often optimised for equipment being on site and therefore minimising duration and costs. The current (standardised) way of working does not allow for optimising on other parameters, such as CO_2. With the increasing focus on environmental impact, insight must be provided the amount of emissions on a project level. This enables a contractor to make quantified decisions about what the most optimal project strategy is for a specific tender. Literature provides limited approaches to assess CO_2 emission, making it difficult for engineers to optimise a project strategy. Therefore the main objective of this thesis is:

To quantify the consequences at project level of CO_2 emission reduction strategies available to contractors, while providing insight in the corresponding financial implications of such strategies

To achieve this research objective, first a literature study is conducted to indicate the possible factors that could contribute in finding strategies that could reduce the emitted CO_2. The indicated factors are divided into two objects: the *project aspects* (determined by the boundaries of the tender: i. dredging and placement location; ii. sailing distance; iii. unloading method, and iv. extraction depth) and the *operational aspects* (determined by the contractor: v. vessel speed; vi. trail speed; vii. unloading production; viii. type of vessel; ix. fuel type) and the *policy measures* (indirectly influence the project strategy of a contractor: x. internalisation of external costs of climate change; xi. adapting regulation regarding project boundaries).

A model is developed to quantify the consequences of strategies available to contractors to reduce CO_2 emissions. To quantify the consequences of strategies, the model objective is to generate: emitted CO_2, project duration, and project costs. By modelling these different aspects, the user can make a data-driven decision on the strategy of a dredging project. The model concept that is chosen is based on the OpenCLSim software package available at the GitHub of the TU Delft Hydraulic Engineering department, which is a rule based planning tool for cyclic activities and in depth comparison of different system components.

The emitted CO_2 is calculated based on the duration and the power consumption per dredging stage. The power requirement is calculated per main energy consumer. The power requirement of the *propellers* and the *inboard dredge pump* is explicitly calculated based on operational parameters and hopper characteristics. The power requirement of other consumers (jet pumps, bow thrusters, and board net) is calculated based on standardised input (Van Oord data) and the duration that the equipment is on site.

The model has shown that there are strategies available to a contractor to minimise the emitted CO_2 within the scope of a project. A base case is simulated to provide a reference to measure the implications of adapting the dredging strategy. With regard to this reference the following strategies are found to reduce the CO_2 emissions. By reducing the vessel speed or by using a different type of vessel, a project can be completed with fewer emissions, -14.9% and -37.9% correspondingly. The effect of reducing the trail speed during loading is also simulated. It is concluded that optimisation in terms of CO_2 is possible when evaluating the dredge pumps separately, yet the reduction effect disappears considering the other energy consumers also operating during the loading stage. The extra time needed for the optimisation, is larger than the optimisation effect. Furthermore, an optimal discharge production can be found which reduces the CO_2 with -7.4%, it should be further investigated whether this is technically feasible.

It has also been demonstrated that it is possible to take policy measures. It is shown that when project boundaries are reconsidered and the contractor is allowed to operate at a different dredging location, CO_2 can be reduced with 15.12%. If the contractor is able to adapt the unloading method and perform a foreshore nourishment instead of a beach nourishment, 55.9 % reduction is achieved.

To conclude, by applying the model to a real case project, the model proved to be useful to the user in optimising a project strategy on CO_2, project duration or project costs. The model quantifies various performance indicators at both high-level (the overall project) and at a low-level (the cycle and specific vessel operations). Making use of the model already increases the area of the solution space that can be analysed by making operational parameters explicit. Yet, further development is recommended to obtain more accurate and detailed results. First, the effects of the weather conditions could be implemented such that the vessel speed depends on actual flow velocities and not only on the absolute velocity. Second, several assumptions concerning the dredging cycle and energy consumption limit the accuracy. To start with, this research has only focused explicitly on the inboard dredge pumps and the propellers as energy consumers. The energy consumption of the other energy consumers is implemented as standardised input, and could be implemented as well.

1 Introduction

1.1. Context

In response to an ongoing trend of increased environmental awareness and a willingness to combat climate change, there is a willingness to reduce greenhouse gas (GHG) emission. This affects the dredging industry, since the execution of dredging projects is associated with a large amount of fuel combustion, and thus GHG emission. To contribute to the reduction of GHG emissions, the dredging industry needs generic methods to provide insight into the energy consumption and corresponding emissions of vessels during a project. This thesis presents an approach which applies energy systems modelling to assess the different strategies of executing a dredging project. The result is a vessel energy systems model that calculates energy consumption, fuel consumption, project duration, and emission predictions.

To start with, more general information is provided about the dredging industry. Afterwards, it is elaborated on how the increased global awareness affects the dredging industry and what this means for future developments.

1.1.1. The dredging industry

Dredging can be defined as the activity of transportation of material from one location of the water environment to another location, transported by specialised equipment, also known as dredging vessels. Dredging projects can have several purposes, where two of the most important purposes are maintenance dredging (i.e., keeping existing watercourses at the required hydrological depth) and capital dredging (i.e., creating new civil engineering works). A dredging project could be set out in the market in the form of a tender. In this tender, the dredging and placement sites are often defined by the contract. A *project strategy* specifies the way of *executing* the dredging project. The strategy is defined by the contractor and is a set of activities with corresponding dredging equipment and project sites. On a high project level, the specification of a project strategy can be described by defining *sites*, *equipment* and *activities*. The dredging and placement sites of the project, the equipment that is used and the activities that specify how the equipment is supposed to move sediment between sites. The most common used type of equipment to execute sand nourishment projects these days, is the Trailing Suction Hopper Dredger (TSHD).

Although sand nourishment with the use of dredging vessels can be seen as an efficient way to combat coastal erosion and protect our properties from flooding, this method has the disadvantage that it is associated with high fuel consumption, and thus the exhaust of GHG emissions. The volume that has to be dredged to maintain the Dutch coastal foundation has been established by law since 1992. The total amount of nourishment volume is $12{\cdot}10^6$ m^3 sand for 2018, and it is advised by the Deltacommission to raise this volume to $85{\cdot}10^6$ m^3 by 2050 (Deltacommissie, 2008) considering an extreme relative sea level rise of 13 mm per year. It is therefore an operation that remains significantly important for our safety, but where, due to the set climate goals, more sustainable solutions must be investigated.

1.1.2. Effects of increasing global awareness on the dredging industry

There was a tipping point in history, concerning the global increase of environmental awareness, when at December 2015, 196 members of the United Nations Framework Convention on Climate Change (UNFCCC) signed the Paris Agreement. The objective includes the *"aim to strengthen the global response to the threat of climate change, in the context of sustainable development and efforts to eradicate poverty"* (UNFCCC. Conference of the Parties (COP), 2015). Holding the increase in the global average temperature to well below 2°C above pre-industrial levels and pursuing efforts to limit the temperature increase to 1.5°C above pre-industrial levels, recognizing that this would significantly reduce the risks and impacts of climate change. GHG emissions contribute to long-term changes in the climate system (IPCC, 2018).

In order to combat climate change and mitigate the GHG emissions, policy makers set goals and come up with measures in the form of legislation. As a response to the Paris Agreement, the Dutch government adjusted its climate policy, and aims for 49% fewer GHG emissions in 2030 than in 1990 (Rijkswaterstaat, 2018). This ambition is visualised in Figure 1.1, where the GHG emissions in the Netherlands for the past years has reported by Statistics Netherlands (CBS) (Centraal Bureau voor de Statistiek, 2017). The rest of this sub-section, provides examples of policy making in the dredging industry concerning these ambitions.

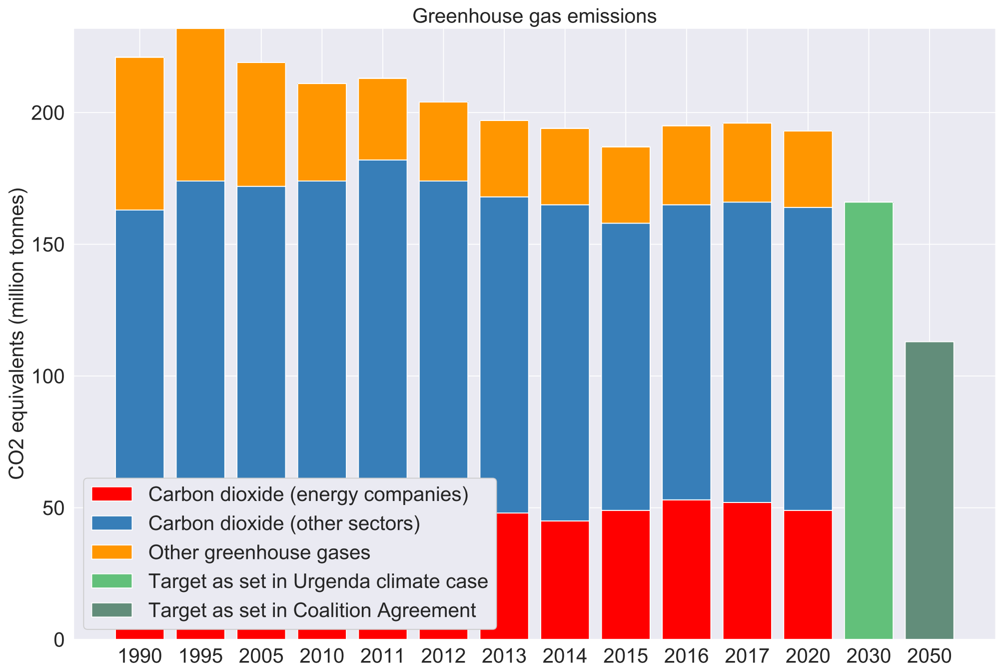

Figure 1.1: Greenhouse gas emissions in the Netherlands. *Source: Centraal Bureau voor de Statistiek (2017)*

Contributing to the mitigation of GHG emissions is not always the most optimal financial way of operating, for a private contractor like Van Oord. Policy makers are thus trying to influence market parties in their decision making by internalising the external costs of CO_2 emissions, and it is likely that this will only develop further in the future (C. A. Kontovas, 2014). A proposal is now being discussed at the Dutch Parliament to introduce such a market based instrument, namely the implementation of a CO_2 taxation system (Het Parool, 2019). In this system, the polluter must pay for each ton of emitted CO_2. A proposal concerns a 80 € tax for each ton of emitted CO_2 in 2020, with an increase of 200 € per ton CO_2 in 2050. This influences the decision making for a dredging strategy, with fuel consumption and the corresponding CO_2 emissions becoming more important incentives than before.

Furthermore, to encourage contractors to work in a more sustainable way, the CO_2 performance ladder was introduced by Rijkswaterstaat (RWS), the Dutch ministry of infrastructure and water management. RWS is the biggest client for projects concerning Dutch coastline preservation in the Netherlands. The CO_2 performance ladder is an instrument with which clients can efficiently assess how seriously a contracting company is working on planned reduction of CO_2. The ladder encourages companies to operate in a climate-friendly way. The more a company makes efforts to reduce CO_2 emissions, the higher it scores on the ladder and the more chance it has of being awarded.

On top of that, more explicit forms of regulations are being applied in the maritime sector. The international emission legislation for the shipping industry has become increasingly stringent in recent years and will become even more stringent in the coming years. Growing environmental awareness and social challenges like air quality, climate change and energy scarcity have resulted in the latest emission legislation as set forth in the International Maritime Organization (IMO) and US Environmental Protection Agency (EPA) regulations. The most recent developed legislation example is the limit that is set by the IMO for sulphur in fuel oil used on board ships of 0.5% m/m (mass by mass) from 1 January 2020 (International Maritime Organization, 2016)).
To express the significance of the amount of GHG emission for the maritime sector: in a report published by IMO (EuDA, 2013), the total emitted CO_2 for 2007 for the maritime sector was estimated to be 3.3% of the total global emissions. This can be seen in Figure 1.2.

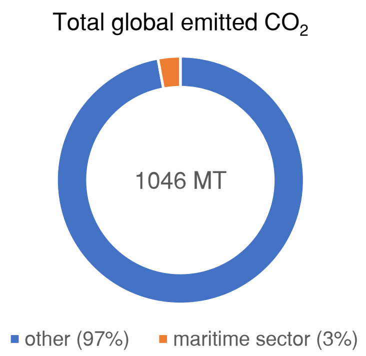

Figure 1.2: Total global emitted CO_2 in 2007. Source: (EuDA, 2013)

Summarising: the ongoing trend of increasing environmental awareness and climate change has triggered policy makers to develop and implement instruments and legislation to encourage sustainability measures and make performing in a sustainable way a business case. The advise of the Deltacommission to raise the amount of sand nourishment volume for the coming decades due to relative sea level rise (RSLR), in combination with the increasingly stringent legislation and with CO_2 emissions becoming more and more an incentive for decision making, makes it necessary to review the conventional way of executing dredging projects. The strategies to reduce CO_2 emission during dredging operations, must be explored.

1.2. Problem analysis

In the current way of working, dredging projects are often carried out as quickly as possible due to high operational costs of the vessels. Due to shifting client requirements and the emergence of potential taxes, it is expected that the project duration will no longer be the most important factor that determines the project costs. With this transition ahead, insight must be provided about the emissions on project level, and about the strategies (at the project level) to reduce the CO_2 emissions. This enables a contractor to make quantified decisions about what the most optimal project strategy is for a specific tender.

Within Van Oord, there is currently no model that provides insights about the CO_2 emissions, and that helps decision making in the tender phase of a project. The lack of insight on CO_2 emission limits the possibilities for engineers to find solutions and test new concepts regarding measures that could be taken to reduce CO_2 emission. In the dredging industry, literature provides limited approaches to assess CO_2 emission on a project level, where operational settings are input variables to the problem. Typically the approach considers *implicit* operational parameters that impact the amount of energy consumption. Such an approach indicates the CO_2 emission, yet it cannot be used correctly to optimise project strategies on CO_2 emission. The use of an indicative method limits the possibilities for engineers to find solutions to reduce CO_2 emissions that are already possible within the conventional way of working.

Problem statement
There is no generic approach or calculation method that is able to assess the emission performance on a project level and is able to quantify the reduction potential within the scope of a given project. The amount of GHG emissions depend largely on the type of project and the corresponding operational settings (i.e., sites, equipment, and activities). Without the assessment of project strategies on project level, it is unknown what emission reduction can be achieved and how cost-effective the emission saving is. The cost-effectiveness of the various measures can be compared to objectively determine which strategy is preferable. Therefore a model must be developed to quantify the emission performance of a project, the potential reduction given the project boundaries, and the corresponding cost-effectiveness of a reduction strategy. This model will be useful to analyse, understand, and reduce the emission performance of dredging projects.

1.3. Research scope

This research is conducted in the scope of a consortium between RWS and various market parties involved with the dredging industry. RWS has put out several tenders on the market concerning reducing emissions and energy neutral operations, to contribute to the Dutch goals of reducing CO_2 emission. The target set by RWS includes achieving a CO_2 emission reduction of 30% by 2020, and being completely energy neutral in 2050.

Sand nourishment projects are responsible for 13% of the total CO_2 emissions in RWS works (Rijkswaterstaat, 2018). For this reason, also a specific tender concerning sand nourishment is developed. This tender is the "Dutch Coastline Challenge" ("Innovaties in de Kustlijnzorg" / IKZ) (Rijkswaterstaat, 2018), and contains a search towards innovative and sustainable ways of executing dredging projects. The tender is about sand nourishment projects completed on the Dutch coast in particular. Where usually the tender is won by the party that is able to perform the project for the lowest cost, this tender goes to the market party that is able to execute the project with the least emitted CO_2. Although this is only one experimenting tender, it indicates a trend in shifting client demand and future policy development.

This research is conducted in the scope of this tender from the point of view of a contractor. Since dredging equipment is the source of the emitted CO_2, more parties are involved than only the contractor when it comes to finding a measure to reduce the amount of CO_2. Both operators, legislators and manufacturers are required in achieving this goal. Although manufacturers widely investigate the development of new clean technologies such as the development of electrical drives, increasing hull efficiency, and alternative energy management systems, the scope of this research leaves out these kinds of measures. The main focus in this research is on finding measures to reduce emissions by exploring the possibilities of operational changes within a project strategy.

1.4. Research objective

The overall research aim is to contribute to the reduction of GHG emissions associated with dredging projects. This research aim reflects the long-term goal of where this research contributes to.

To contribute to this research aim, a more specific research objective is defined. This entails the development of a model, to assess the amount of emissions of a dredging project, executed with a specific project strategy. In the scope of a particular dredging project it is often not known what the reduction potential of emissions is. By exploring this reduction potential, conventional dredging operations can be optimised in terms of emission or new technologies and applications could be tested. The financial implications of implementing a reduction measure must also be investigated. The second objective of this research is thus to provide insight into the financial implication of the emission reduction potential of dredging projects. The purpose of the model is to provide the user with reliable insight in both the number of emissions and the financial implication in terms of project cost, allowing the user to make a quantified decision about adapting the project strategy. Finally, it is wished for that the development of the model leads towards a standard approach of assessing environmental impact of project strategies. This can be summarised in the following research objective:

To quantify the consequences at project level of CO_2 emission reduction strategies available to contractors, while providing insight in the corresponding financial implications of such strategies

To achieve this objective, the following research questions are formulated:

(i.) Which factors determine the CO_2 emissions during a dredging project, and which of these factors can be influenced by a contractor?

(ii.) Which methods are available to quantify CO_2 emissions in dredging projects?

(iii.) How to develop and validate a model to assess the CO_2 emissions performance and corresponding financial implication of a project strategy?

(iv.) What are the quantitative contributions of different factors that influence the CO_2 emissions at project level, and what is the corresponding financial implication of these factors?

(v.) What part of the desired emission reduction can be achieved by optimising project strategies?

1.5. Methodology

This section outlines the methodology that is used to conduct this research. The various steps that are taken are: conducting a literature study, data collection and gathering, development and validation of a model, and testing the model by applying it to a case study.

The literature study is conducted to indicate the factors that determine the emitted CO_2 during a dredging project, but also to determine which of these factors can be influenced by a contractor. It answers the first research question. During the literature study, state of the art emission estimation models are reviewed. The combination of these two analyses provide insight into the model set-up, and the model's functional requirements.

The next step in the research is data collection. Analysing the impact of strategies on the total amount of emissions on a project level is only possible if the required data is available about dredging projects. Project boundaries determined by the tender, equipment characteristics, and available production and fuel data must be gathered.

After the information is collected, the model is developed and validated. This answers the third research question. After the model is successfully developed and validated, it is able to quantify the impact of strategies and the corresponding financial implication. The simulation model is used to answer the fourth research question. The effects of the strategies on the emission levels is analysed. Additionally, the results should provide insight into which factors play an important role in the contribution to the reduction ambition of RWS. With these insights, the final sub-question is answered.

1.6. Guide to reader

An outline of this thesis is presented in Figure 1.3 in which the various research objectives are highlighted. Chapter 2 answers the first two sub-questions, resulting in an overview of all the important factors that need to be integrated into model set-up. The third sub-question is answered in Chapters 3 and 4, in which the first chapter describes the model specifications, structure, and a concise overview to inform the reader of relevant processes and engineering knowledge that is needed for the simulation of a dredging project. Chapter 4 provides information about the approach and results of the validation of the model. To conclude with the answer to the fourth sub-question of this research is described in Chapter 5. In this chapter, the application of the model is tested on a case project and the results of various strategies to reduce the amount of emissions of dredging projects are presented. In the last Chapter, number 6, the conclusions, point of discussions and recommendations for further research are listed.

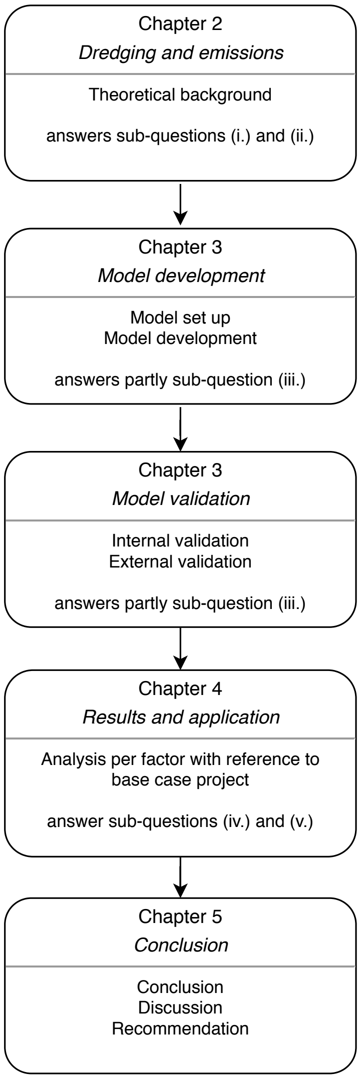

Figure 1.3: Structure of the report, presented per chapter and research question

2
Dredging and emissions

This chapter answers the first two sub-question of this research:

Which factors determine the CO_2 *emissions during a dredging project, and which of these factors can be influenced by a contractor?*

Which methods are available to quantify CO_2 *emissions in dredging projects?*

To answer these research questions, a literature study has been performed to determine all factors that influence CO_2 emissions during dredging projects. To find measures that reduce the emitted CO_2 for a dredging contractor, it is analysed which of these factors can be controlled by a contractor during the execution strategy of a project. The result of these analyses are listed in Section 2.1. In Section 2.2 an overview of the state of the art emission assessment methods are presented. To conclude, the answers to the first two research questions are formulated in Section 2.3.

2.1. System analysis

This section intends to provide insights into the relation between dredging and emission. In addition, it provides insights into the possibilities and limitations that a contractor such as Van Oord has to reduce emissions.

To start with, the basic relation between dredging and emissions is discussed briefly. The execution of a dredging project is associated with a large amount of fossil fuel combustion, and thus CO_2 emissions. The total amount of fuel combustion depends on the power required by the equipment and the duration that the equipment is operating on site.

The strategy to execute a project is partly determined by the contractor itself, but limited by the boundaries of a tender. It is important to note this distinction because the boundaries of a tender limit the solution space for the contractor to reduce CO_2 emissions. To illustrate the solution space for reducing CO_2 emission during dredging projects, a process flow of different project stages is shown (Ecoshape, 2019) in Figure 2.1. During the initiation of a project, the tender is put out on the market. For Dutch coastline projects, this is normally done by RWS. The boundaries of the tender (partly) affect the planning and design phase since the dredging and placement locations are already determined. The playing field of the contractor includes the planning and design phase (limited), the construction phase, and operation and maintenance phase of the project. Within these stages, the contractor is able to explore the possibilities of measures that can be taken to reduce the emitted CO_2. To conclude the system analysis, a third category is indicated. This is *policy measures*, which is an external incentive to influence decision making for the selected work method. These incentives indirectly influence the emitted CO_2. The factors that determine the boundaries of the tender are further referred to as *project aspects*, and the factors that are still to decide by the contractor are further referred to as *operational aspects*. The three categories are further discussed in the rest of this section.

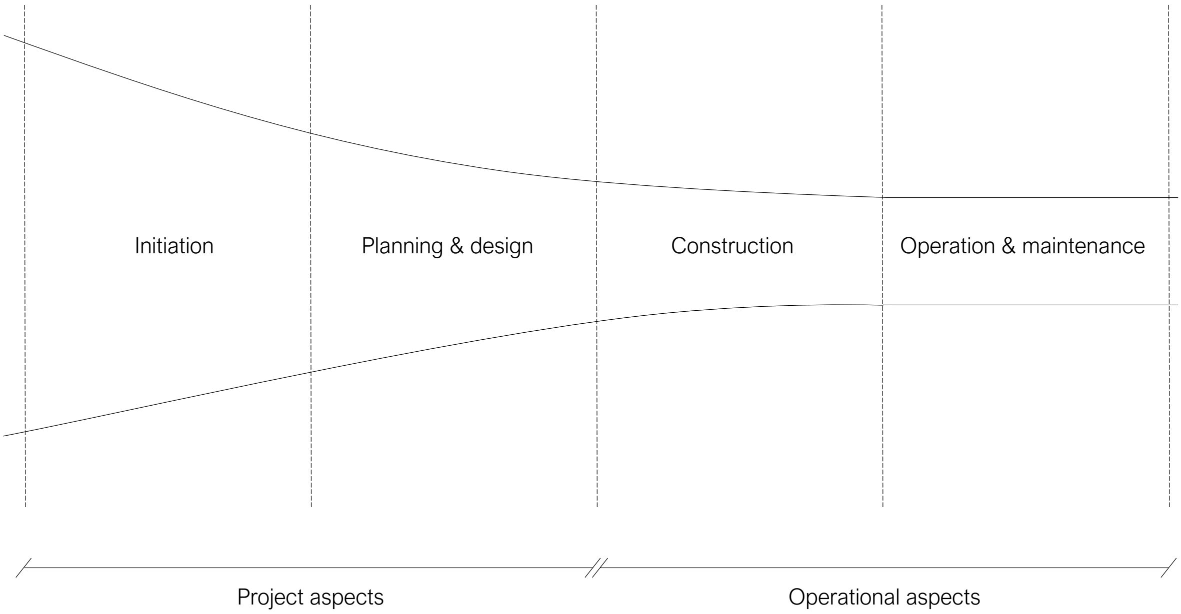

Figure 2.1: Project process flow (Ecoshape, 2019)

A literature study has been conducted to indicate the *project aspects*, *operational aspects*, and *policy measures* that influence the total emitted CO_2. An elaborated actor analysis on energy efficient coastline preservation by Rijkswaterstaat (Kollen, van den Ouden, & van den Heuvel, 2011) and expert interviews at Van Oord, indicate the optimisation possibilities. This analysis provides a basis for determining which of the parameters discussed here should be included in the set-up of the model. Each parameter is briefly discussed.

(i.) Project aspects

- *Sailing distance:*
  The sailing distance is determined in the tender since the placement location and the dredging area are determined. The sailing distance is in general the shortest route, with available accessibility for the chosen ship type, between these two points. The larger the sailing distance, the larger the amount of energy consumption during the sailing stages of the production cycle. Large sailing distances, increase the project duration and the fuel consumption during the sailing stages. This will increase project costs.
- *Extraction depth:*
  Extraction depth is at least more than 20 meters for beach nourishment projects, since it is determined by law that dredging is only allowable outside the coastal foundation (Rijkswaterstaat, 2019). The larger the extraction depth, the more energy is required to get the material on board on the vessel, and thus more emissions are expected. An increase in extraction depth gives an increase in required loading time and pipeline resistance resulting in higher fuel consumption and thus higher project costs.
- *Material to be dredged:*
  The type of soil and consistency of the material has an impact on the(un)loading phase of the production cycle, since it influences the critical velocity and the settling process and thus the project duration and energy consumption. More energy is required to transport relatively coarse material (van der Schrieck, 2016). Yet the cumulative overflow losses of coarse material are less than the overflow losses of fine material (Miedema & Vlasblom, 1996). The exact settling process is also determined by the vessel dimension. With the same hopper assumed, yet the settling process of coarse material requires less time than the settling process with fine material. This effects the project costs.

– *Unloading method:*
The amount of volume that is needed for coastline preservation yearly, is divided in a part for beach nourishment and a part for foreshore nourishment. The type of nourishment partly determines the type of unloading method. Unloading by dumping is only possible for foreshore nourishment, and requires less energy than the other methods (Gonçalves Castro, Ooijens, & Van Ingen, 2014). For beach nourishment, pumping or rainbowing could be applied, where the contractor tries to unload the ship as quickly as possible. The emissions differ per unloading method. The relatively quick process of dumping gives the least emissions. Rainbowing and pumping are associated with higher emissions. The quantify of emissions depends on corresponding pipeline resistance a pump has to overcome. The time needed to unload the ship effects the total costs of the ship. The costs for the the consumed fuel depend on the energy consumption during the unloading stage.

(ii.) Operational aspects

– *Sailing speed:*
Dredging vessels often sail at maximum speed during a project, due to high operational costs of a vessel. Sailing at lower speeds corresponds to fewer emissions. Reducing the absolute vessel speed can be achieved by decreasing the engine speed. The operational costs for equipment being on site will increase when the vessel speed decreases, since the equipment will be longer on project site. Yet the fuel consumption decreases with a decrease of vessel speeds.

– *Trail speed:*
During the loading stage of a dredging vessel, the trail speed and the available vacuum determine the loading production. In current practice the highest production is tried to be achieved during this stage, by increasing the trail speed to the point of maximum production. The higher the production during loading, the earlier the ship is filled with dredged material. Yet, assuming that the contractor is operating at the most efficient point, higher production corresponds to higher pipeline resistance. This is further elaborated in Chapter 3. The increase in pipeline resistance results in higher hydraulic power requirement given a certain flow, which influences the energy consumption. The vessel resistance also increases with an increase in trail speed. Higher fuel consumption and a larger amount of emitted CO_2 are expected with an increase of trail speed during loading. The high production rates that correspond with a high trail speed, decrease the time of the equipment being on site. Yet the costs for the consumed fuel depends on the energy consumption, and are expected to decrease with a decrease of trail speed.

– *Unloading production:*
During the unloading stage of the dredge cycle, current practice aims for achieving the highest unloading production. A higher unloading production results in higher resistance due to previously described effect on the pipeline resistance. High unloading production rates , decrease the time of the equipment being on site. Yet the costs for the consumed fuel depend on the energy consumption, and are expected to decrease with a decrease of unloading production.

– *Hopper loading rate:*
The process of (un)loading can be optimised in terms of duration by stopping the (un)loading process the moment the discharge production is lower than the total cycle production that is reached at the same moment. In current practice, this process is visualised on board with a *Loading- and Offloading curve (m^3/s)* for the crew member of the vessel, so that they are able to indicate this specific moment. The hopper loading rate optimises the cycle time and determines the load that the vessel carries. The more the vessel is loaded, the larger the draught of the vessel, which influences the accessibility of the vessel. The hopper loading rate thus effects the logistics, the production, and the energy consumption of the vessel during operations.

– *Type of vessel:*
A contractor such as van Oord possesses different types of ships available for carrying out nourishment projects. A distinction between TSHDs is often made on the basis of their capacity: small - medium - large - jumbo. Which ship is ultimately deployed depends on availability and decisions from higher management. The larger the vessel size, the more material per trip can be transported and the energy consumption per cubic meter of material could decrease with an increasing vessel size. On the other hand, larger vessel sizes correspond mostly to more power installed on board

of a vessel. Furthermore the amount of energy consumption depends a lot on vessel characteristics, what makes it necessary to analyse the energy consumption per ship with the corresponding operational settings of the project. The most significant ship characteristics are the installed drive systems, efficiencies of the main energy consumers, and vessel's dimensions. The vessel's dimensions effect the ship's accessibility and thus the length of the discharge pipeline. A conclusion about the amount of energy consumption per ship type can only be made within the scope of a project. Larger vessel sizes correspond to relatively higher vessel costs due to higher exploitation costs of the vessel. More crew members are needed for a larger ship. Due to relatively more power installed, a larger vessel is expected to consume more fuel.

- *Fuel type:*
  The amount of emitted CO_2 depends directly on the type of fuel, since the carbon content and the energy density of the fuel differ per fuel type. In current practice diesel fuels like Heavy Fuel Oil (HFO) and Marine Diesel Oil (MDO)are most often used. By using a more sustainable fuel (biofuel, liquefied natural gas (LNG), Hydrogen), fewer emissions could be achieved when using diesel fuels. Due to the production pathways and, more sustainable fuels are generally more expensive than conventional fuels used in the dredging industry. Yet it is expected that the costs of renewable fuels will decrease with further development of technologies. The high capital costs associated with changing the type of fuel used, are another barrier for a contractor.

(iii.) Policy measures

- *Fuel price developments*
  Policymakers try to internalize the external costs of CO_2, by for example the increase of fossil fuel prices. Increased fuel prices lead towards more energy efficient operations, and a further reduction in emissions. Studies of (Corbett, Wang, & Winebrake, 2009) and (Lindstad, Asbjørnslett, & Strømman, 2011) found an relation between vessel speed and emission reductions, and state that it effects the decision making of the operator. Research has shown that a fuel tax of about 150 US dollars per ton would lead to a CO_2 reduction of 20 - 30 %.
- *Environmental pricing*
  The same effect on the market as with an increase of fuel price, is likely to hold for implementing an CO_2 taxation system.
- *Adapting project boundaries*
  The dredging location and placement location are determined by the tender to maintain the coastal foundation. The coastal foundation is the zone between the dunes and sea dike and the ongoing Normal Amsterdam Level -20 meter depth line in the sea. The maintenance of the volume of sand in this coastal foundation is determined by law since 1992. This policy indirectly determines the project aspects of the tender, since the dredging location must be positioned outside the zoning of the coastal foundation, and the placement location determines the unloading method. Adapting these project boundaries, could offer optimisation opportunities.

2.2. Approaching emissions in dredging

In this Section, an overview of the state-of-the-art emission assessment methods are presented, to determine the model set-up for this thesis. The methods presented are: an indicative emission estimation method presented by the Central Dredging Association (CEDA), and a method based on average power consumption presented by the IMO. The different methods are briefly discussed, after which they are evaluated based on the applicability to the dredging industry.

Indicative CEDA method
An indicative method is presented in a study concerning emissions in dredging operations (Loboyrie et al., 2018). In this method, several cases are calculated with different discharge methods and TSHD size categories.Table 2.1 lists the results of the CO_2 footprint per case.

Table 2.1: Indicative CO_2 emissions (in kg CO_2 / situ m3) removed soil) for different TSHD size (expressed as maximum load in Dry Weight Ton, DWT) and dredging operations. The numbers are based on a reference dredging cycle based on a 18.5 km (10 nautical miles) sailing distance to and from the discharge area. The numbers presented here reflect the maximum and minimum value of emissions within a statistical envelope of emission representing 85% of the European Dredging Associate (EuDA) fleet Loboyrie et al. (2018).

TSHD size categroy	**Reference cycle, discharge via bottom doors**	**Reference cycle, pumping (1 km)**	**Reference cycle, rainbowing**
	Emission rates in kg CO_2 /situ m3 removed soil		
<4,000 DWT	3.9 - 2.0	4.0 - 2.5	3.7 - 2.4
4,000 <DWT <8,000	3.4 - 1.9	3.6 - 2.4	3.5 - 2.3
8,000 <DWT <16,000	3.2 - 1.7	3.5 - 2.3	3.4 - 2.2
16,000 <DWT <32,000	3.0 - 1.6	3.4 - 2.2	3.3 - 2.2
32,000 <DWT	2.8 - 1.4	3.2 - 2.1	3.2 - 2.1

The presentation of these numbers is a first in the dredging industry, and makes it possible for engineers to get an indication of the emission at project level. The advantage of using this method is that with few input parameters, it can quickly provide an estimate of the amount of CO_2 at project level. The disadvantage of this method is that it partly takes away the possibility for an engineer to explore the solution space. To illustrate this problem: the vessel's speed is, as has been shown in the literature research, a parameter to reduce the CO_2, and this is implicitly incorporated in this method.

IMO Approach

To find the amount of GHG emissions that are produced during a project, a method is presented by IMO (Stapersma, Kramers, & Verheijen, 2009), specially developed for the maritime industry. In this method the total CO_2 emissions are a function of the main and auxiliary engines averaged power consumption. The CO_2 emission are weighted against the *benefit of society*, which is the transported amount of sand. This is represented by the volume that is transported and the speed of the vessel. The Energy Efficiency Design Index (EEDI) formula is found in Equation 2.1.

$$EEDI = \frac{\left(\sum_{i=1}^{nME} C_{FMEi} \cdot SFC_{MEI} \cdot P_{MEI}\right) + P_{AE} \cdot C_{AE} \cdot SFC_{AE}}{Deadweight \cdot V_{ref}} \tag{2.1}$$

Where:

C_F	=	the conversion factor for a specific fuel type	(kg emission / kg fuel),
SFC	=	Fuel Consumption	(kg / kWh)
P	=	Average power consumption	(kW)
Deadweight	=	Maximal carrying capcity of a vessel	(TDS)
V_{ref}	=	Vessel speed	(knots)

It has been investigated in various research topics how using this method would turn out in the dredging industry specifically (Stapersma et al., 2009), (Gonçalves Castro et al., 2014). The main objections for using this method to indicate CO_2 emissions in the dredging industry are as follows. The formula focuses on the reduction of installed power. This can be concluded because the fuel consumption is not calculated explicitly, but based on average installed power. Another objection for the use of this formula, is that it is not applicable for all type of equipment, since the *deadweight* factor is for example not an issue for cutter dredgers, and the speed is not an issue for backhoe dredgers. The last objection against the usages of this formula within the dredging industry, is that it does not include the impact of the variation between operational conditions of a dredging project. The dredging cycle varies per project. In the study conducted by (Stapersma et al., 2009), recommendations are formulated to adapt the EEDI formula, and develop a method that includes the main parts of the dredging cycle: *sailing empty to the winning location, dredging, sailing filled to the discharge location*, and *discharging*. The energy consumption should be incorporated per phase of the dredging cycle, and the denominator can be left out of scope to compare various types of equipment.

The usage of the *adapted* formula of the IMO could be used to indicate the amount of emission during the total dredging cycle. The advantage of this method is that, when data about the average power consumption for the fleet of Van Oord is available, it can quickly estimate the amount of CO_2 at project level based on this historical data. The disadvantage of this method is that it partly takes away the possibility for an engineer to explore the solution space. Since the usage of average power consumption of a vessel does not take into account the project specific boundaries, the solution space to find measures to reduce the emission, decreases.

2.3. Conclusion

The conducted literature study resulted in the indication of various aspects that determine the emitted CO_2, and answers the first research question. The factors are distinguished between the *project aspects* (determined by the boundaries of the tender) and the *operational aspects* (determined by the work method strategy of the contractor) and the *policy measures* (indirectly influences the work method strategy of a contractor). This analysis has provides a basis for determining which parameters should be included in the model set-up.

Two methods have been suggested by literature to indicate the level of emissions during dredging operations. The first is an indicative method presented by CEDA. The second is based on average consumption. Although both methods provide quick indications of emissions based on standardized input, and are applicable within the method's boundary conditions, both methods do not include all parameters that are important for project CO_2 emission as noted in the literature study. Part of the solution space in the tender phase of the project for engineers decreases and possible optimizations cannot be found. This indicates that a model must be developed in which all the specified parameters or Section 2.1 must be taken into account. The next Chapter elaborates on the model development.

3
Model Development

This chapter answers the model development part of the third sub-question of this research. Together with the next chapter the research question is answered in total.

How to develop and validate a model to assess the CO_2 emissions performance and corresponding financial impact of a work method?

This is done by by first determining the model objective, the functional requirements, and the model's structure presented in Section 3.1. Section 3.2 explains in detail which input parameters are included in the model and thus which data must be collected to use the model. Section 3.3 includes all calculations that are used by the model to generate output. Section 3.4 presents an overview of the output that can be generated with the model. Section 3.5 presents the conclusion of this Chapter and an answer to the research question.

3.1. Model outline

The objective of the model is formulated in Sub-section 3.1.1. Based on the literature study, a set of functional requirements is derived as listed in Sub-section 3.1.2. The chosen model concept is explained in Sub-section 3.1.3. In Sub-section 3.1.4 an overview of the developed model structure is provided.

3.1.1. Model objective

To quantify the emitted CO_2, and financial impact of a dredging project, a purposely built model was developed, capable of translating a dredging project into key performance indicators concerning the emission performance and financial impact. This translation is done based on a predefined *work method*. A work method is a set of standardized project input, classified by *equipment*, *activities*, and *sites*. With this set of input, the model is able to describe the logistic processes of the project and the performance indicators. This translation can be seen as a series of discrete events, which translate the standardized input of a work method into configurations. In other words, the model simulates how a dredging project is executed following the specifications of the work method. This chapter will elaborate on how the model comes to such an outcome, explaining what aspects are fed into the model and how this can be used to evaluate a work method.

The environmental impact of a dredging project, denotes the GHG emissions that play a role in global warming, presented as the $CO_2 - eq$. These emissions are the result of the emission content of fuel and fuel combustion. The amount of released CO_2 is related to the energy consumption of a work method. Therefore the focus in the model is on energy performance and the environmental impact is post-processing of this data.

When referring to the financial performance of a work method, we refer to project costs, which consist of the operational costs that result from activities that need to be performed during a dredging project, and can consist of several items. This thesis focuses on the operational costs of equipment of a project, which are part of the so-called production costs of a dredging project. In some scenarios simulated, the indirect costs are also part of the financial performance. In this thesis the indirect costs refer to the environmental prices associated with fuel combustion. Environmental prices are prices that calculate the marginal social value of preventing emissions, or interventions. Environmental prices thus indicate the loss of welfare due to one additional kilogram of pollutant. These environmental prices can be used in the application of social cost-benefit analysis and can play a crucial role in decision making.

All in all the objective of the model is to quantify the level of emission, the financial impact, and the project duration of dredging projects.

3.1.2. Functional requirements

Based on the literature review of Chapter 2 and the model objective, a set of functional requirement is formulated. The functional requirements are listed and further explained below. The model must be able to:

(i.) *Support the user in finding emission reduction measures.*
When project boundaries are stated in where the level of CO_2 is an important incentive, the model must support the user in finding measures to optimise in terms of emissions. Therefore, all factors mentioned in the system analysis which have an influence on the amount of CO_2 during a project must be integrated into the model, in order to estimate the emission associated with different work methods.

(ii.) *Support the user in decision making on project level.*
Since it is expected that the optimal work method in terms of CO_2 is not the same work method as the most optimal work method in terms of financial impact, the model must be able to quantify the financial impact that the choice for a work method has. The financial impact of the measures that can be taken should be quantified as well so that the user can make a data-driven decision for the optimal strategy.

(iii.) *Provide down-drilled insight.*
The simulation model should be able to simulate each project stage, to provide a down-drilled insight in the level of emissions per project stage: sailing empty, dredging, sailing filled, and unloading. This makes it easier to analyse the impact of different work methods on the emitted CO_2.

3.1.3. Modelling concept

As Chapter 2 concluded, to assess a dredging project on CO_2 emissions, the model must be able to simulate the logistics and energy consumption of a dredging project. Therefore, the model needs to represent the project properties. Furthermore, the model must meet the functional requirements, listed in Section 3.1.2. The model concept that is chosen is the Open Complex Logistic Simulation (OpenCLSim) available at the GitHub of the TU Delft Hydraulic Engineering department (van Koningsveld, den Uijl, Baart, & Hommelberg, 2019), which is based on a combination of Discrete Event Simulation (DES) and Agent Based Simulation (ABS). It is developed in a dedicated Simpy environment in Python. The reason for this concept is twofold. First, this package has already been tested and proved to be useful for the simulation of dredging projects within Van Oord. Secondly, it reduces the computational time when a lot of work methods must be simulated. Furthermore, the functional requirements and the characteristics of the dredging cycle meet the characteristics of the combination of DES and ABS. The motivation is further discussed in this section.

First, the OpenCLSim is tested and it is proved to be useful within Van Oord. It is developed to support the user in making logistical decisions when projects get complicated (den Uijl, 2017). It has already been successfully utilized for the estimation of source terms (Becker et al., 2015). Moreover, the simulation of plume development, and for the planning of building a layered dike (den Uijl, 2017). For the research in this thesis, further specification and development of this method will be done, to be applicable for the estimation of CO_2 emissions during the execution of dredging projects in the Netherlands. The model is being developed for Van Oord engineers, and for the chances of success with regard to implementation, it is therefore important that it matches the current practice within Van Oord.

Secondly, this concept is chosen because the functional requirements and characteristics of a dredging cycle suit the combination of DES and ABS. The project flow of a dredging project can be seen a series of discrete events, where the equipment in the model can be seen as autonomous entities (agents) and can display proactive behaviour. With ABS the actions and interactions of the agents can be modelled with a view to assessing their effects on a dredging project as a whole. As such, an agent based simulation model is a set of interacting objects (sites and equipment) that reflect the relationship between vessels operating between sites, while transporting soil. DES evaluates the evolution of a system as a discrete sequence of events in time. Each event occurs at a particular instant in time and may mark a change of state in the system (Law & Kelton, 2013). This method can be seen as a widely used simulation method for studying industrial and planning processes. (Wohlgemuth, Page, & Kreutzer, 2006). Once a simulation is validated correctly, it is assumed that these models can increase the understanding of the behaviour of a system (Law & Kelton, 2013). In many processes, especially in the context where *events* can be easily distinguished, DES has proven to be a use-full method. These contexts are for example manufacturing, transportation, inventory management, supply chain operations, and also ship routing and scheduling. All these examples consist of discrete components like machines, whose behaviours cause state change through discrete events that typically be dispersed randomly along a model's timeline (Wohlgemuth et al., 2006). In the simulation of a dredging cycle, discrete components can also be recognized, namely the *equipment*. These components behave accordingly to the state in which they occur, which can also be seen as events. The events in which they operate can either be dredging, sailing full, placement of the sand or sailing empty.

In contrast to its popularity for modelling logistics, DES has not yet been widely used to analyze environmental issues like emissions (Wohlgemuth et al., 2006)(Christiansen, Fagerholt, Nygreen, & Ronen, 2013). But Wohlgemuth presents in his research in 2006 a method that integrated discrete event simulation and material flow analysis in a component based approach to industrial environmental protection, which is proven to be a viable method. Also, (Ahn, Pan, Lee, & Pena-Mora, 2010) present a methodology to integrates DES into the emission estimation model in order to enhance the credibility of the emission estimation. They prove that the reliability of the emission estimation for construction operation can be improved in two different ways. First, it provides statistically reliable estimates on operating hours of each piece of equipment. Second, project characteristics and the way that projects are executed are integrated with the simulation that ensures a more realistic utilization rate of equipment that is incorporated in the standard emission prediction tools (i.e. the IMO approach described in Chapter 2).

3.1.4. Model structure

This section covers how the model creates the desired output of the environmental and financial impact of a dredging project, and explains what aspects are fed into the model and how this can be used to evaluate various work methods. Each aspect will be explained in separate sub-sections. In Figure 3.1 the overview of the model, all the processes and how they are interlinked is shown. This can serve as a guideline to keep the overview for reading the following sub-sections in the section.

3.2. Input data

The structure of the model is divided into *activities*, *equipment*, *sites*, and *costs*. In this section, each component is briefly explained in a separate sub-section, and each sub-section is concluded with an overview of all the necessary input data that must be specified for running a standard simulation. The input is used for the calculations of the model (section 3.3) to generate the output (section 3.4.

3.2.1. Activities

The developed OpenCLSim package, makes it already possible to simulate the logistics process of a dredging project. The following section briefly explains how this works and what the possibilities and limitations are. This is all based on a previously published thesis work (den Uijl, 2017). This enables a perspective for developing and implementing the energy consumption functions within the OpenCLSim. It is necessary to properly understand the basis of the package to understand the choices for developing and implementing the energy functions.

When analysing the logistical process of a dredging project, various events can be distinguished. The events are: sailing empty, dredging, sailing full, and the placement of the material. A project is finished after a number of repetitions of this cycle, namely when all the material that should be transported is indeed transported. To simulate the logistical functions of a dredging project, specification of the sites and the equipment have to be defined in the model together with a set of conditions and boundaries. In the first place, to determine

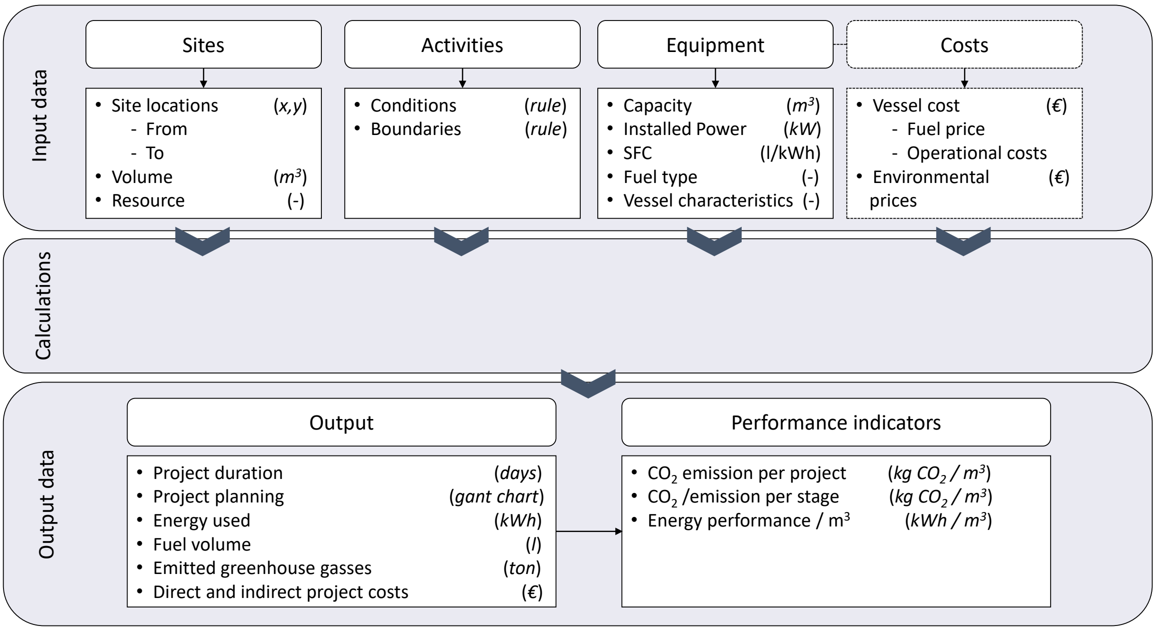

Figure 3.1: Structure of the model

a basic activity, sites and equipment have to be selected. A dredging site and a placement site have to be implemented between where equipment can operate. To define equipment, specifications about the type of operations must be added to the equipment. Within the scope of a dredging project, two different types of equipment are defined. Equipment can either be, in terms of functionality, a transporting agent or a dredging agent. A dredging agent is able to process material (i.e. a Cutter Suction Dredger (CSD) or a Backhoe dredger (BHD)), while a transporting agent is able to transport the material from one location to another (i.e. split TSHD barge). In other cases, the equipment can both transport and process material (i.e. TSHD), and the equipment is then able to complete a whole dredging cycle by itself. A basic simulation requires specifications on the number of resources of each project site, and it is possible that the TSHD cannot be served upon arrival at either the dredging site or de placement site, because for example, another vessel is operating at that location. For this situation, the possible event waiting on site is created. Figure 3.2 shows a schematic representation of the dredging cycle with a trailing suction TSHD dredger, where thus the transporting agent is also the dredging agent.

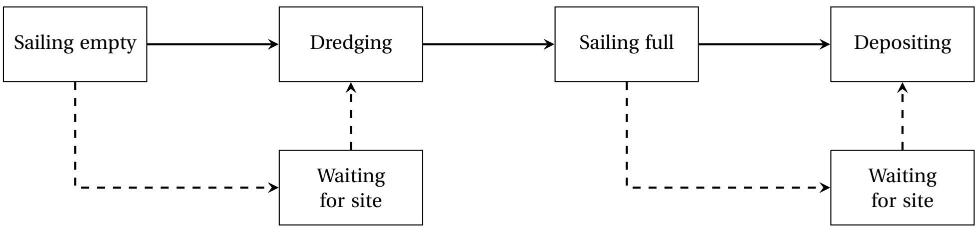

Figure 3.2: Dredging cycle for simulations where a dredging agent is also a transporting agent (i.e. TSHD) (den Uijl, 2017)

Similar events occur for a dredging cycle with an independent dredging agent and transporting agent. However, with a separate dredging agent and transporting agent, the dredging agent remains at the dredging site. Therefore the event waiting for site cannot occur for the dredging agent once a dredging cycle has started. However, a separate dredging and transporting agent does introduce two new events; waiting for transporting agent and waiting for serving. If the dredging agent cannot continuously dredge, it is idle for the time that no transporting agent is available. In the case that the dredging agent is continuously dredging, there can be a queue of transporting agent waiting to get served. The waiting for serving time is defined as the difference between the arrival time of the transporting agent at the dredging site and the time that the dredging agent starts discharge into the transporting agent. Figure 3.3 shows a schematic representation of the dredging cycle with a separate dredging agent and transporting agent.

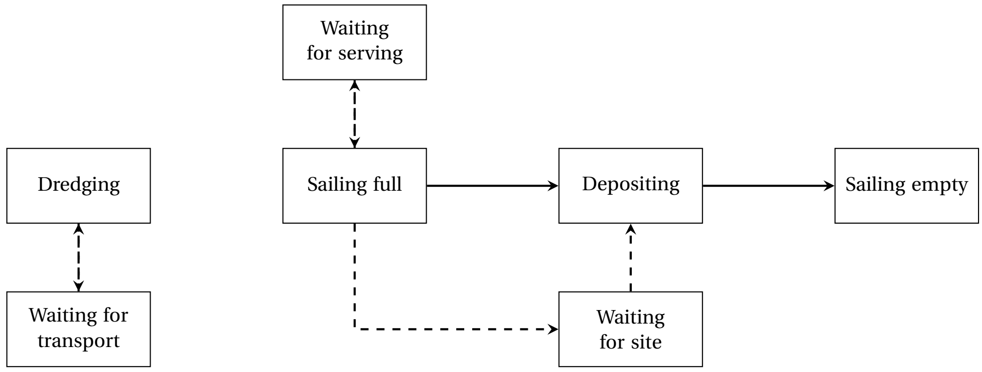

Figure 3.3: Dredging cycle for simulations with a separate dredging agent and transporting agent (i.e. BHD with barges) (den Uijl, 2017)

To complete the simulation settings, rules need to be defined. These rules consider, for example, when a project is finished. In the most basic case, this is when the placement site is filled with the required sand of the dredging site. However, in more challenging simulations, time restrictions can be added. An example concerns operations can only take place during a specific time window, in terms of minimizing nuisance during certain hours. For a basic simulation, the activities that need to be defined are listed in Table 3.1.

Table 3.1: The required input for project activities

Activities	
Dredging agent	[*Vessel*]
Transporting agent	[*Vessel*]
Dredging site	[*site*]
Placement site	[*site*]
Condition	[*rule*]

3.2.2. Equipment

While the equipment performs the production cycle, it consumes energy. The energy is obtained from the combustion of fossil fuels and therefore GHG are emitted, including CO_2. The duration of the production cycle, and the amount of energy that is consumed depend on the vessel characteristics. This section provides background information about the energy consumers on a TSHD, and concludes with an overview of the TSHD characteristics that are used during production and energy consumption calculations, see section 3.3.

To provide more information about the energy consumption on board of a TSHD, this section explains what the main energy consumers are and how they function. The distribution of the total required power multiplied with the duration of an event of the production cycle yields the total energy consumption of that event. The power distribution depends on the machinery configuration of a dredging vessel and the required power of all the consumers during the different stages of the operational profile. The machinery configuration provides the power for the dredge pumps, jet pumps, propellers, bow thrusters and board net. The configuration of the installed main and auxiliary drives to generate this power can vary and is strongly related to the vessel configuration. Often used machinery configurations vary from direct drive to an all-electric ship. In the conventional dredging vessels, the main and auxiliary drives are the only energy producers on board, making a vessel self-sufficient when it comes to generating energy. The mechanical energy that is produced by the combustion of fuel is distributed by either mechanical or electrical means to the consumers. The shaft rotation speed of the drives is usually constant since this enables an alternator to produce a continuous output frequency. The load determines the specific fuel consumption (g/kWh) which relation is the most essential characteristic of the drives when it comes to fuel consumption calculations. Based on the load factor and the intermittent rating the fuel consumption can be calculated. The load factor is a measure of the average required energy data of a consumer compared to the maximum theoretical input and can be calculated by dividing the average power by the peak power. The intermittent rating is the ratio of the required power consumption over some time and reflects the time the power consumer is switched on.

Identifying leading consumer categories within the machinery configuration and evaluating their operational usage will help to provide insight into the energy distribution. For the TSHD the main consumers categories are as follows:

1. **In-board dredge pumps**
   The most common used type of in-board dredge pump is the centrifugal dredge pump, which is used for the hydraulic transport of soil with water. The pumps are only used during the loading and unloading stages of the dredge cycle. The centrifugal dredge pump is one of the biggest energy consumers on board of a TSHD and acts in a pipeline system where it adds a specific pressure head H to a certain flow Q.

2. **Underwater dredge pumps**
   Large TSHDs, which operate at relatively large extraction depth, are equipped with underwater dredge pumps installed on board. The power demand is comparable with the power demand of in-board dredge pumps. An underwater dredge pump is often used in combination with an inboard pump to deal with the under pressure necessary for the suction process.

3. **Jet pumps**
   The jet pumps inject water under high pressure into a mixing tube, creating a pump action. The jetting process involves the erosion of (non-cohesive) soil types, also known as loose grained soils. The loosened soil that is lifted is known as jet production. The jet pumps operate during the loading and unloading phase. In the loading phase to loose the in situ soil, and during the unloading phase to liquidize the sand in TSHD.

4. **Bow thrusters**
   The bow (and stern) thrusters can be used to position the vessel accurately during manoeuvring. The vessel is manoeuvring when it is trying to get its position for dredging or unloading of a load. During the sailing phases, the heading of the ship is changed by adjusting the rudder angle, and the bow and stern thrusters usually are not operated.

5. **Board net**
   The board net of a vessel can be seen as the vessel's power grid, that is required to support the vessel's operations. The board net contains the electricity for all the smaller consumers (e.g. lights, coffee machine). The board net is operating during all the dredging stages.

6. **Propulsion system**
   The ship's propulsion system is fully operating during the sailing stages. The propellers are also working during the dredging stage since the TSHD must reach a certain trailing speed to be able to achieve a particular production. The power demand for the propulsion of the vessel depends on the required speed and the vessel's resistance.

The required power per dredging stage is estimated during the design of a vessel. The energy demand of the main consumer categories depends on the dredging stage, and the expected load factor per stage. These predicted values can be used to estimate the power consumption during the dredge cycle. This can be implemented in the OpenCLSim by providing the installed power on a vessel as input value. The load factor is highly depend on the operational conditions of the dredging project, but with fuel logs, an average load factor is found for the primary consumers per dredging stage. The advantage of using the average load factors is that little data is needed to make an initial estimate for the assessment of various work methods, with still a down-drilled insight. An example of the power distribution on board of a TSHD and the corresponding energy distribution based on load factors within Van Oord can be found below, where Figure 3.4 shows the power distribution on board of a medium-sized vessel and 3.5 shows the energy consumption of this vessel when it is operating. This last Figure shows the power distribution multiplied with the duration of the corresponding event. These values correspond to a typical dredging project for the Dutch coastline preservation, with a sailing distance of 10 kilometres, a dredging depth of 30 meters and a medium sized TSHD.

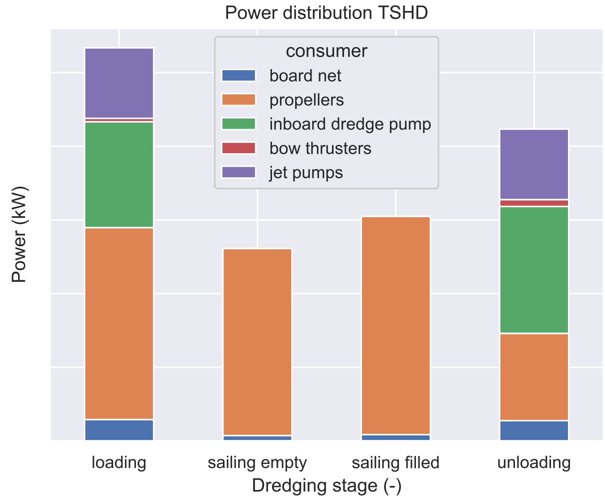

Figure 3.4: Power distribution of a TSHD

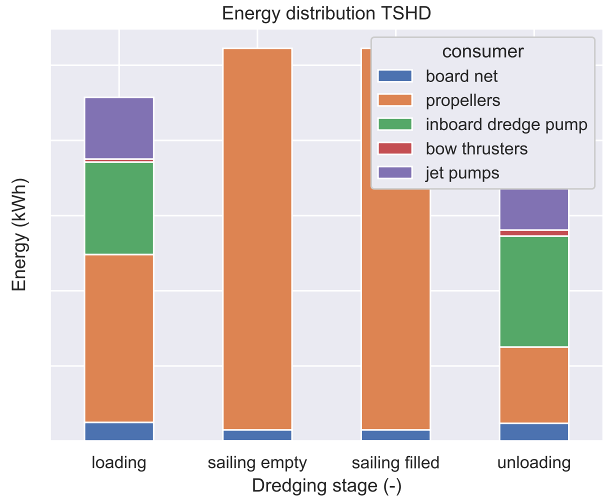

Figure 3.5: Energy distribution of a TSHD for a standard project

Insights on the energy distribution based on load factors is a useful method since it provides an initial estimate about the total consumption. The disadvantage is that with a set value of the load factors the power demand is not calculated by the power requirements based on operational parameters. In this way, you are not able to simulate and quantify variations of the parameters. This reduces the possibilities to find measures for the increase of energy efficiency and the reduction of the carbon footprint of a project. It is for this reason that the energy consumption for the primary consumers is determined by the requirement based on a parametric model, which is elaborated on in the next section. This enables the user to also optimise in terms of energy consumption.

The required input parameters to calculate the production and the energy consumption of a TSHD are listed in Table 3.2. In Section 3.3, it is shown per stage how the duration and the energy consumption is calculated.

Table 3.2: The required input for equipment

Equipment	
Vessel name	[*string*]
Installed power (per consumer)	[*kW*]
Load factor (per consumer per stage)	[*%*]
Specific fuel consumption	[*l/kWh*]
Fuel type	[*string*]
Capacity	[m^3]
Vessel speed loaded (actual and max)	[*m/s*]
Vessel speed unloaded (actual and max)	[m/s]
Trail speed	[*m/s*]
TSHD loading rate	[*%*]
Unloading method	[*string*]
Unloading production (when pumping or rainbowing)	[m^3/s]
Extraction depth	[*m*]
Vessel pipeline characteristics	[-][a]

[a] The vessel pipeline characteristic are: width of the draghead (w); jet penetration depth (h); number of suction pipes operating (n_s); length of the suction pipe (L_s); diameter of the suction pipe (D_s); loss factor for bends in suction and discharge pipeline (ξ_s, ξ_d); distance pump center to waterline (A); inlet loss factor (α); length discharge pipe (L_d); diameter discharge pipe (D_d); porosity of the dredged material (n); density of the dredged material (ρ_s)

3.2.3. Sites

In a dredging project, sand is replaced from a winning area to a disposal area. This has to be adequately represented in the model, by defining sites. In the model, it should be defined, if the specific location is a placement site or a dredging site. A volume has to be assigned to each site V (m^3). By determining the required amount of volume, a specific project can be defined. It can be set at which point in time, the project is finished (when all the sand is replaced from the dredging site to the placement site). Another parameter that needs to be defined for the sites is the amount of resources. The number of resources n (-) represents the number of agents that can get served simultaneously at the same site; in this way, the operational activities of the vessels can be included. In Table 3.3 the required input for the sites is listed.

Table 3.3: The required input for project sites

Sites	
Site name	[*string*]
Location	[*coordinate*]
Volume	[m^3]

3.2.4. Costs

This section provides background about the costs associated with the execution of a dredging project. The section concludes with a list of the input required for the simulation is given.

An estimation of the project costs by the contractor requires several things. The specifications of the work need to be analysed; this is usually done be a production estimator. In this phase, a working method that is to be used is selected. It is determined how the dredging project can be executed, and the activities that need to be performed are translated into costs. The cost estimator collects all the necessary information about the costs items. Afterwards, the proposal price is calculated. In this proposal price, the most common cost items include:

- **Mobilisation and demobilisation;**
  The equipment of Van Oord operates all over the world. The mobilisation and demobilisation costs consist mainly of costs incurred to transport the vessel from the old operating area to the new area. It

can take a few weeks for a vessel that sails an average of 13 knots to come from the other side of the world. The local presence of a vessel enables a contractor to hand in a competitive bid.

- **Weekly production costs**
  - Depreciation and interest;
    The amount of depreciation (D) and interest (i) of the equipment, are also known as 'lease'. The lease depends on the investment expenses incurred, the utilisation rate, the period of depreciation and the interest on the capital market. Typically for a TSHD, according to (van der Schrieck, 2016), the yearly utilisation rate is 33 weeks/year and D+i = 9. 647 %.
  - Maintenance and repair
    The maintenance and repair costs are also included in the proposal price. The wear and tear costs are calculated based on assumptions on the execution of projects throughout a whole year. The assumptions concern the operating hours per week, the material that is dredged. The pipes are an example of a high-cost item within a dredging project.
  - Crew
    To execute the project as fast as possible, the equipment must be on operating constantly, preferable 168 hours per week. This is achieved by having multiple shifts, where crew members alternate each other. When working constantly is allowed, four shifts are used. The number and origin of the crew members determine eventually the total costs. To give an order of magnitude, a Dutch crew member costs 3000 € per week (including tickets, pay also during leave and local housing and care) and a local crew member costs 1000 € per week. On a large TSHD 15 to 30 crew members can be operating.
  - Fuel and lubricants
    The consumption and the price per litre determine the fuel expenses. The fuel consumption for modern diesel engines is approximately 0.2 litre per kWh. The average price for Marine Diesel Oil is approximately 0.65 €(Chryssakis, 2013). The costs of the lubricants can be estimated to be 10% of the fuel costs.
  - Insurance A common norm for the insurance expenses is between 0.004% and (including damage) 0.007% of the value norm for weekly insurance expenses.
- **Capital expenditure;**
  Perchance, it may be that new equipment (i.e. vessels or pipelines) is purchased for the execution of a particular project,. If a select type of equipment has to be bought to execute a project, this can be part of the proposal price.

Table 3.4 shares an example of cost calculation for a beach nourishment project. It is an example of how costs can be integrated in the model. The model user must enter the cost of the equipment per week and the fuel price. The model determines the total amount of weeks that a vessel is on site, and the amount of fuel consumed. If environmental prices are considered as well, an extra cost item must be added.

Table 3.4: Example project costs TSHD

Project: **Beach nourishment (1,000,000 m^3)**		
Weekly expenses	Depreciation and interest	€ 293,372.4
	Maintenance and repair	€ 103,484.1
	Crew	€ 61,000
	Fuel and lubricants	€ 74,000
	Insurance	€ 41,137 +
		€ 572,993.5
Total project costs	Mobilisation 1 week	€ 773,000
	Execution (4.8 weeks)	€ 2,750,368.8
	Demobilisation 0.5 week	€ 386,500 +
Total		€ 3,909,868.8
Cost per m^3		€ 3,9

In the scope of this thesis work, only the weekly costs of the ship are included. These costs are subdivided into fuel and lubricants, and the rest of the weekly costs. Although fuel normally falls under weekly costs, it has been decided to separate the two. This was chosen because the project duration and amount of energy consumed are also separate functions within the model, and therefore not directly dependent on each other. The (de)mobilisation costs, and extra expenditures for capital expenditure are not included. This is because the model compares different work methods, where the focus is on the execution of a project. The tool can be further developed, whereby the cost functions can be classified as the given example. This enables a down-drilled insight for the cost estimators when different simulations are executed. An additional cost item that is integrated in the model, is the environmental price. The possibility exists for the implementation of costs per kg emission, which is used to test the impact of environmental pricing on the work method. In Table 3.5 the input for the project costs is listed.

Table 3.5: The required input for project costs

Costs	
Weekly expenses (ex. fuel and lubricant)	[€/*week*]
Fuel and lubricants	[€/*volume*]
Environmental price	[€/*kg*]

3.3. Calculations

This section elaborates on how the model obtains the amount of emissions per event, by providing an overview of all the used equations. In sub-section 3.3.1 an introduction about the various stages is given, and information is provided on general calculations of the model. In sub-sections 3.3.3, 3.3.2, and 3.3.4, more specific information on the calculations concerning the energy consumption and duration per stage of the cycle is provided.

3.3.1. Basics of the dredging cycle

For implementation in the model, the dredging cycle is split up in discrete events, and a distinction is made between the various dredging stages. The main reason for doing this, is because the required power differs per event. The different cycle components must be calculated separately, to provide insights in this difference power requirement. The respective stages that are simulated with the model are: dredging, sailing full, unloading, and sailing empty. A project is finished after n repetitions of the dredge cycle. In Equation 3.1 the formula for the total project duration is shown, assuming no downtime.

$$\text{Project duration} = \sum_{i=0}^{n} (t_{dredging} + t_{sailing\ full} + t_{unloading} + t_{sailing\ empty}) \tag{3.1}$$

The total cycle duration is visualised in Figure 3.6. The figure shows only one dredging cycle, where the different cycle stages are identified by the different colours. As can be noted in the Figure, the (un)loading stages consist of two stages. During the first stage of the loading process, a sand-water mixture is loaded until the overflow level is reached. Afterwards the loading continues while overflowing. At this point, for material with low density (i.e. silt) the efficiency of the loading process starts to fall, deflection of the loading curve can be seen, see Figure . For coarse material, where it can be assumed that almost everything settles in the TSHD, (almost) no deflection can be detected in the loading curve. During the unloading phase, there will also be such an offloading curve when using the discharging system of the TSHD by pumping or rainbowing, this can also be seen in the Figure. After some time, the discharging production is lowered because of an increasing lack of sand in the TSHD. When dumping by means of opening the doors, the cycle time will be much shorter, and this will result in a steep unloading line in the figure.

Now that it has been derived how to calculate the duration per dredging stage, the energy consumption per stage can be calculated. To be able to calculate the energy performance, it must be known how much power is required by each main consumer. If the average required power per main consumer per stage is known, the energy consumed can be calculated according to Equation 3.2.

$$\text{Energy consumption} = \sum_{i=0}^{n} (P_{load} \cdot t_{load} + P_{sfull} \cdot t_{sfull} + P_{unload} \cdot t_{unload} + P_{sempty} \cdot t_{sempty}) \tag{3.2}$$

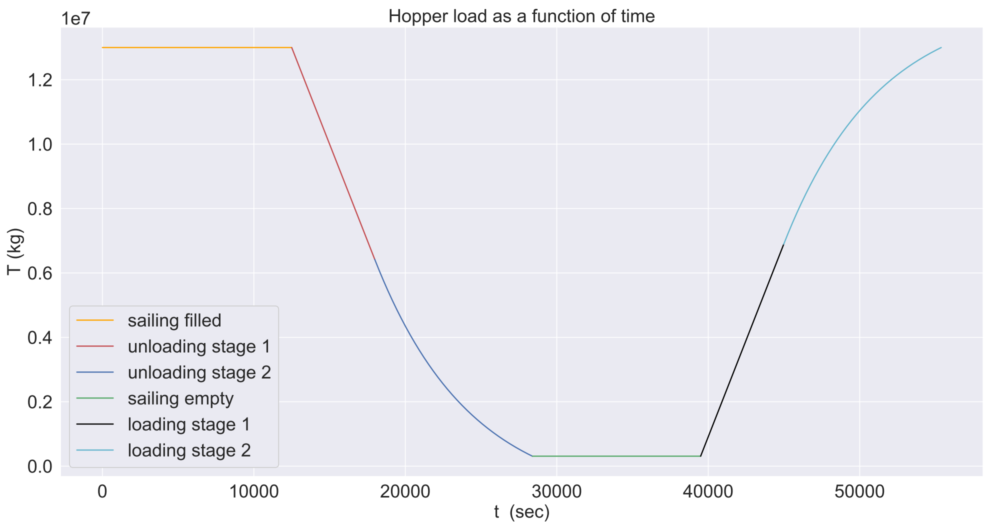

Figure 3.6: Loading curve (kilograms versus time) of trailing suction TSHD dredger with fixed overflow height

The total power required during a certain phase of the dredging cycle depends on which consumers are requiring power during that phase. Table 3.6 provides an overview of which main users are working in which phase of the dredging cycle.

Table 3.6: Active main consumers per dredging stage

	Loading	**Sailing filled**	**Unloading**	**Sailing empty**
Inboard dredge pumps	x		x[a]	
Propellers	x	x		x
Jet pumps	x		x	
Bow thrusters	x		x	
Board net	x	x	x	x

[a] The inboard dredgepumps are not working when dumping is the used unloading method

The amount of power that is required per energy consumer depends on the operational conditions and the efficiency losses of the corresponding consumer and the engine. A schematic overview of the efficiency losses can be found in Figure 3.7. In the next sections, it is shown how the energy consumption is calculated per event. This involves looking at how much energy is required per main energy consumer. In the calculations, the requested power is explicitly calculated for the propellers and the inboard dredge pumps. For the other main users (jet pumps, bow thrusters, board net), fixed values have been adopted based on available data from Van Oord per equipment. The reason that it has been chosen to adopt these parameters as constants is as follows. The bowthrusters and the boardnet are relatively small consumers, and therefore offer significantly less opportunity to be part of an emission reduction measure. Based on expert interviews within Van Oord, it is also recommended to set the jet pumps as a fixed value because it is difficult to estimate how the power of the jets affects the bottom profile. The consequence of this is that the jets are completely turned on or off during operations. For the main consumers that are set at fixed values a corresponding factor is implemented in the model per dredging event. This factor is a percentage of the installed power of that specific consumer. This factor includes the average demand of power per energy user for that specific stage and the efficiency losses of that consumer. This factor per main consumer is based on fuel consumption logs. With this data a rough estimation can be made about the total energy consumption per standardized in a dredge cycle.

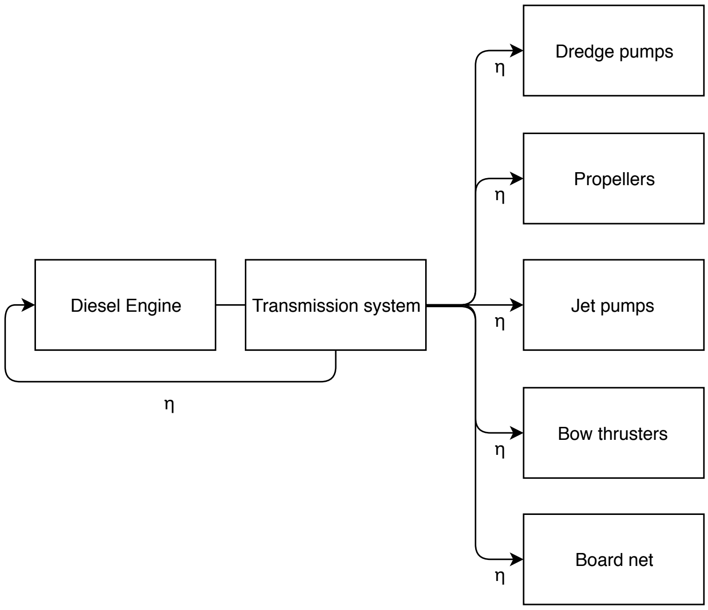

Figure 3.7: Schematic overview of efficiency losses and main energy consumers

With the energy consumption per stage, the amount of fuel that is consumed and the emitted CO_2 can be calculated. To find the amount of CO_2 emitted during a project, a method is presented by IHC (Stapersma et al., 2009). In this method the fuel consumption is multiplied with a fuel type specific emissions factor (C_f) since emissions are directly related to fuel consumption. This expression is shown in Equation 3.3. The term CO_2 equivalent ($CO_2 - eq$) is often used in literature. This quantity signifies the amount of CO_2 that would have the equivalent global warming impact. Any quantity of GHG can be expressed as $CO_2 - eq$ by multiplying the amount of the GHG by its global warming potential (GWP).

$$CO_2\text{-eq} = C_f \cdot SFC \cdot P \cdot t \tag{3.3}$$

Where:

CO_2-eq	=	amount of emissions	(kg)
C_f	=	the conversion factor for a specific fuel type	(kg emission / l fuel),
SFC =	=	Specific Fuel Consumption	(l / kWh)
P =	=	Effective power (including all efficiency losses)	(kW)
t =	=	the time the power is required operating time	(hours)

The conversion factor differs per type of fuel. In the past decades, increasingly sustainable fuels have been developed as an alternative to the older (fossil) fuels. Today, most vessels at Van Oord run on Marine Diesel Oil (MDO) and Marine Gas Oil (MGO), but two LNG TSHDs on the way. The conversion factors for different fuel types can be found in Appendix A.

3.3.2. Loading stage

During the loading stage, all energy consumers are in operation. Equation 3.4, shows the equation for the total energy consumption during the loading stage. In this section it is further explained how the loading duration is calculated and how the total power requirements of the propellers and the inboard dredge pumps are calculated.

$$E_{load} = \sum_{i=0}^{n} t_{load} \cdot (P_{inboard} + P_{propellers} + P_{jet\,pumps} + P_{bow\,thrusters} + P_{board\,net}) \tag{3.4}$$

To obtain the loading duration and the power required by the inboard dredge pumps, the production rate must be calculated. In the loading phase of the production cycle, the dredge pumps deliver a certain production over a discharge pipeline lengths. The maximum production can be either limited by the available vacuum or by the available jet production. Therefore the lowest value of the two is ultimately the normative production that can be reached.

If the jet production is lower than the production of the available vacuum, the vacuum can be reduced. This reducing this vacuum, the required head that the dredgepump need to deliver reduces. In Figure 3.8, the production lines are plotted for various available vacuums. Each point on each line corresponds to a combination of mixture density and pipeline velocity where, for the calculated production, energy losses are minimal van der Schrieck (2016).

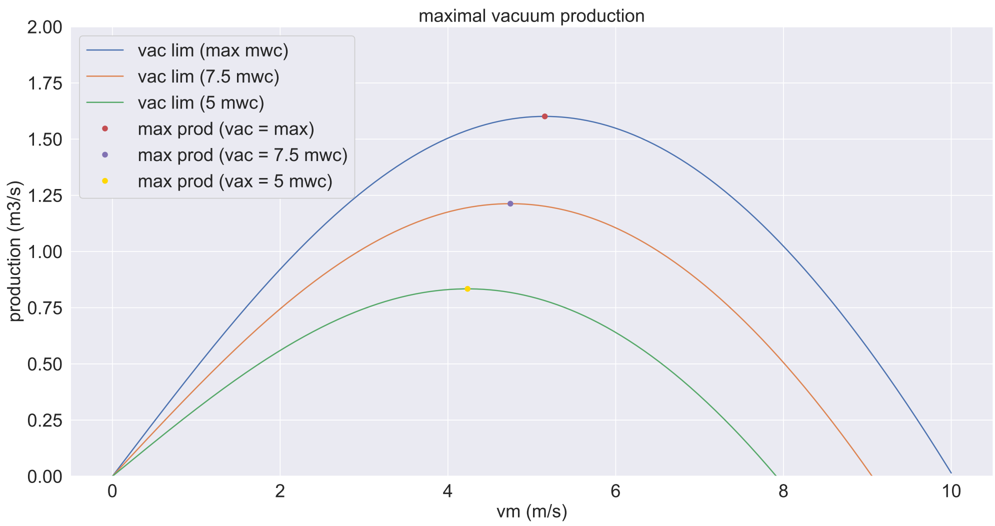

Figure 3.8: Maximal production with varied available vacuum

In Figure 3.8 the maximal production points are plotted for each vacuum. Connecting all the maximal production points of a range of vacuum limits, results in the optimal vacuum production line. Each point at this line represents a combination of mixture density and pipeline velocity of a production where energy losses are minimal. In Figure 3.9, this optimal production line is plotted.

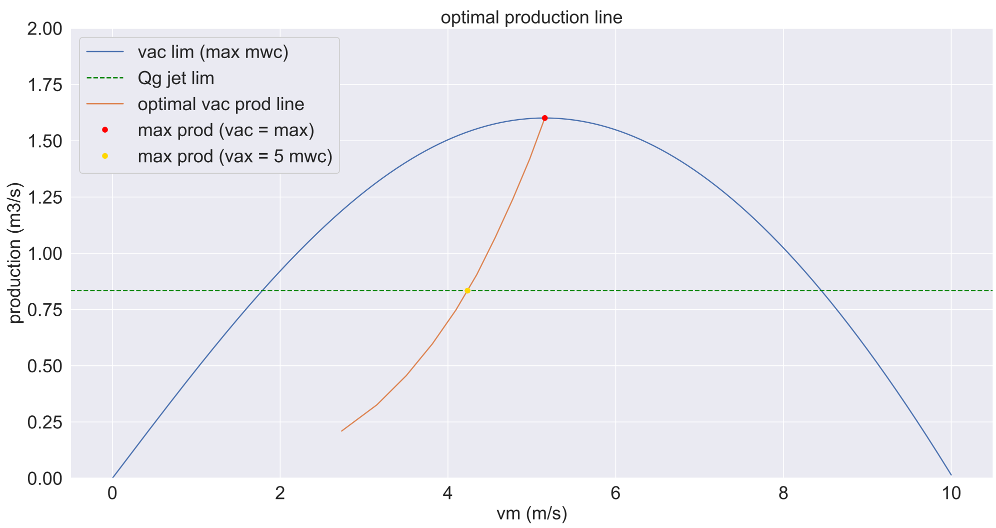

Figure 3.9: Optimal production line

To obtain the most efficient work point and the corresponding vacuum, the vacuum production equation is combined with the jet production equation. This is implemented in the model as that the production is equal the vacuum production, Equation 3.5 and the jetting production, 3.6. Afterwards, the corresponding necessary vacuum is calculated with the suction formula 3.19.

$$Q_{g\ vacuum} = C_v \cdot \frac{1}{1-n} \cdot f_t \cdot v_s \cdot \frac{\pi \cdot D_s^2}{4} \tag{3.5}$$

$$Q_{g\ jet} = v_{trail} \cdot w_{draghead} \cdot h_{penetration\ depth} \tag{3.6}$$

Where:

$Q_{g\ vacuum}$	=	production at the available vacuum	(m^3/s)
C_v	=	volume of grains divided by the volume of the mixture	(-)
n	=	porosity	(n)
f_t	=	transport factor	(-)
v_s	=	sediment velocity	(m/s)
D_s	=	diameter of the suction pipe	(m)
$Q_{g\ jet}$	=	production of the jet	(m^3/s)
v_{trail}	=	trail speed of the TSHD	(m/s)
$w_{draghead}$	=	width of the draghead of the TSHD	(m)
$h_{penetration}$	=	penetration depth of the jets	(m)

The volumetric concentrations that correspond to the vacuum production depend on the density of the the mixture, see equation 3.7. The production is part of a total mixture flow that depends on the velocity of the mixture and the area, see equation 3.8. When TSHDs are operating with two suction pipes, and one discharge pipe, the corresponding discharge velocity an flow can be calculated according to 3.9 and 3.10.

$$C_v = \frac{\rho_m - \rho_w}{\rho_s - \rho_w} \tag{3.7}$$

Where:

ρ_m	=	mixture density	(kg/m^3)
ρ_w	=	density of the water	(kg/m^3)
ρ_s	=	density of the grains	(kg/m^3)

$$Q_m = A_s \cdot v_m \tag{3.8}$$

$$v_d = \frac{Q_m \cdot n_s}{A_d} \tag{3.9}$$

$$Q_d = v_d \cdot \frac{\pi \cdot D_d^2}{4} \tag{3.10}$$

Where:

A_s	=	area a the suction pipes	(m^2)
v_m	=	velocity of the mixture	(m/s)
n_s	=	number of suction pipe(s) operating	(-)
n_d	=	number of discharge pipe(s) operating	(-)
A_d	=	area of the discharge pipe	(m^2
D_d	=	diameter of the discharge pipe	(m)

To calculate the optimal vacuum production, this volumetric concentration and the mixture density must be determined. This can be obtained using the suction formula 3.11 by calculating the maximum feasible mixture density and the associated production at a certain vacuum level for several pipeline velocities. Per flow velocity a combination with a mixture density is found for which the production is maximum for that flow velocity. The maximum production that can be achieved is the maximum production of all these production rates found. This line can be interpreted as the combination of production and pipeline velocity where the energy losses are minimal and the production is maximum, which results in the most efficient way of working.

$$\rho_m = \frac{(Vac + Z) \cdot \rho_w}{(1 + \alpha + \xi_s + \lambda \cdot \frac{L_s}{D_s}) \cdot \frac{v_s^2}{2g} + (Z - A)} \tag{3.11}$$

Where:

Vac	=	available vacuum	(mwc)
Z	=	extraction depth	(m)
ρ_w	=	density of the water	(kg/m^3)
α	=	inlet loss factor	(-)
ξ_s	=	resistance factor of non straight parts	(-)
λ	=	resistance factor of straight parts	(-)
L_s	=	length of the suction pipe	(m)
D_s	=	diameter of the suction pipe	(m)
v_m	=	velocity of the mixture	(m/s)
g	=	gravitational acceleration	(m/s^2)
A	=	depth of the submerged pump relative to the waterline	(m)

The production for a specific project can be calculated and optimised with the discussed formulas depends on the operational parameters of the specific project. The duration of the loading phase, depends heavenly on the settling process. Several computational models are discussed in literature to calculate the settling process. Since this research is about optimizing and testing possibilities, it has been decided not to elaborate on such a computational model. The settling process can be modelled with a settling curve and the model is structured in such a way that it accepts a settling curve as manual input. Allowing calculations to be made accordingly.

The first stage of the loading process is when the loading stage starts until the overflow level has been reached. The duration of the first stage can be calculated using Equation 3.12, and the formula for the corresponding load can be found in Equation 3.13. If dredging continuous after reaching the overflow level, the second stage starts. The more the TSHD gets filled with material, the higher the velocities above the settled material will be, and therefore more material stays in suspension and more material will leave the TSHD. This is shown in the deflected part, stage two of the loading part in the graph of Figure 3.6. How this process exactly is evolving in time, depends on the size of the TSHD and the dredged material. To give an indication on how this process behaves, a formula like Equation 3.14 can be used. For coarse material, where it can be assumed that everything settles, a very high factor can be assumed, to have zero overflow losses. For the more fine grained material, a lower factor is more appropriate. In the example a factor of 1.2 times the overflow time is given. Based on expert knowledge and data about the filling process of the TSHD, an appropriate loading curve can be constructed.

$$t_{overflow} = \frac{V}{Q_d} \tag{3.12}$$

$$\frac{T}{dt} = (Q_d \cdot C_s \cdot \rho_{situ}) \qquad for\ t < t_{OV} \tag{3.13}$$

$$\frac{dT}{dt} = (-Q_d \cdot C_s \cdot \rho_{situ}) \exp\left(-\frac{t - t_{OV}}{loading factor}\right) \qquad for\ t > t_{OV} \tag{3.14}$$

Where:

t_{OV}	=	the time until overflow	(sec)
V_{TSHD}	=	the volume of the TSHD	($m3$)
Q_d	=	the discharge flow	(m/s)
C_s	=	apperent concentration	(-)
T	=	in situ weight of material (effective load)	(kg)
ρ_m	=	density of the discharge mixture	(kg/m^3)
$loading factor$	=	the loading factor that determines the deflection of the TSHD	(-)

To optimise production, it is common practice that the loading process is ended when the weight of the vessel (T) has reached the maximum loaded vessel weight (N.B.: max. at dredging mark) or when the actual loading production (dT/dt) reaches the the total cycle production (T_{load}/t_{cycle}). Both these constraints are implemented in the model. The total time ($t_{dredging}$) that is returned by the model is the total loading time, that consists of the two stages.

Now that the relation between the loading duration and the production is explained, the calculations of the required power of the inboard dredge pumps is further elaborated. To transport the material, the inboard dredge pumps needs to deliver a certain amount of head to overcome the pressure difference that is necessary to transport the material from one location to another. The required head is delivered by the pump in terms of pump power, see equation 3.15. The engine power will lose some power when converting to hydraulic power depending on the efficiency of the discharge, see Equation 3.16. The efficiency is a function of the flow and the mixture density, as shown in Equation 3.17. Where $\eta_{Q_{water}}$ expresses the efficiency at a certain flow, which is known based on Q-η characteristics for a specific pump.

$$P_{hydraulic} = \rho_w \cdot g \cdot Q \cdot (\Delta H_{man}) \tag{3.15}$$

$$P_{shaft} = \frac{P_{hydraulic}}{\eta_{inboard\ dredgepump}} \cdot n_s \tag{3.16}$$

$$\eta_{inboard\,dredgepump} = \eta_{Q_{water}} \cdot \frac{\rho_{mixture}}{\rho_{water}} \tag{3.17}$$

The pressure difference consist of the vacuum before the pump, also known as the suction side of the pump, together with the discharge pressure behind the pump. The total pressure difference that a pump delivers is also known as the total manometric head, and can be found in Equation 3.18. The suction formula, to calculate the vacuum, is shown in Equation 3.19, and the pressure behind the pump can be calculated according to formula 3.20 (van der Schrieck, 2016).

$$H_{man} = Vac + \frac{n_d}{n_s} \cdot H_p \tag{3.18}$$

$$Vac = (1 + \alpha + \xi_s + \lambda \cdot \frac{L_s}{D_s}) \cdot \frac{v_s^2}{2g} \cdot \frac{\rho_m}{\rho_w} - (Z - A) \cdot \frac{\rho_m}{\rho_w} - Z \tag{3.19}$$

$$H_p = (\xi_d + \lambda \cdot \frac{L_d}{D_d}) \cdot \frac{v_d^2}{2g} \cdot \frac{\rho_m}{\rho_w} + (H + A) \cdot \frac{\rho_m}{\rho_w} + \frac{v_d^2 - v_s^2}{2g} \cdot \frac{\rho_m}{\rho_w} \tag{3.20}$$

The relation between the trail speed, the vacuum, the pressure behind the discharge pipe and the total manometric head can be found in Figure 3.10. With increasing vessel trail speed, the production increases. The vacuum is calculated based on this production. It is shown that a higher vacuum is needed when the trail speed increases. The discharge pressure behind the pump also increases when the production increases, which results in an increase of total manometric head. This is an example where two suction pipes, and one discharge pipe is operating, where thus half of the pressure behind the discharge pump is delivered by the dredge pump.

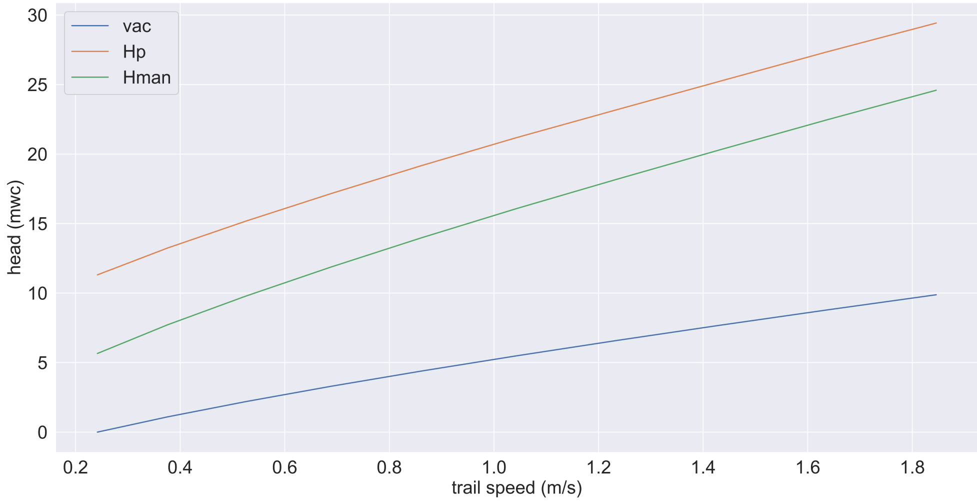

Figure 3.10: Pressure head delivered by one single pump for various trail speed (configuration: one discharge pipe and two suction pipes operating)

During loading, the suction tubes are operating and provide extra resistance. The propellers should be able deliver additional power to deal with this resistance. The propulsion force that needs to be delivered is in equilibrium with the horizontal trailing force and the horizontal force that attributes to the water resistance of the vessel. The formula that is used to calculate the horizontal force, is discussed in detail in the following sub-section about the sailing stages. The horizontal trailing force consists of the forces that attribute to the water resistance of the suction tubes, the horizontal forces between the drag head en the bed, and the horizontal cutting or jetting forces on the edges or teeth in the drag head (van der Schrieck, 2016). Based on fuel logs, the power that is required for the propellers during sailing is known within Van Oord per equipment type. This data is used to represent the power that is needed to overcome the total horizontal trailing force. Although it depends on the aforementioned factors it is assumed to be constant. These parameters remain constant because the range in which the trail speed increases when testing the model is small (v_{trail} = 0 - 1.5 m / s). With only a small adjustment of the trail speed, the trail force also varies minimally. In subsequent research this relation can be added for an even more accurate power estimation. In the current state of the model, the power required by the propellers during dredging can be calculated as shown in Equation 3.21, where the power related to the trailing force is a constant, and the power related to the water resistance of the vessel is a function of the vessel speed, which is explained in the next sub-section.

$$P_{propeller} = P_{trailing\,force} + P_{water\,resistance\,vessel} \tag{3.21}$$

3.3.3. Sailing stages

During the sailing stages, the energy consumers that are assumed to be operating are the propellers and the power required for the board net. Equation 3.22, shows the equation for the total energy consumption during the sailing stages. In this sub-section it is further explained how the sailing duration is calculated and how the total power requirements of the propellers are calculated.

$$E_{sailing} = \sum_{i=0}^{n} t_{sailing} \cdot (P_{propellers} + P_{board\,net}) \tag{3.22}$$

To derive the sailing time, $t_{sailing\ full}$ and $t_{sailing\ empty}$, the vessel speed and the sailing distance must be known. The sailing distance is the distance between the win location and the dump location of the project. The formulas for the sailing times, are shown in Equation 3.23 and 3.24.

$$t_{sailing\,filled} = \frac{s}{v_{filled}} \tag{3.23}$$

$$t_{sailingempty} = \frac{s}{v_{empty}} \tag{3.24}$$

Where:

s	=	sailing distance	(m)
v_{filled}	=	vessel speed when filled	(m/s)
v_{empty}	=	vessel speed when empty	(m/s)

From data within Van Oord the maximum vessel speeds are measured for all vessels in two different stages. For the vessel being loaded with maximum load at the dredging mark, and measurements also have been taken for the vessels being empty. Taken realistic operations into account, when for example the loading process of the TSHD is stopped when max production has been reached, it can be stated that the TSHD is not always completely full or completely empty. Since no more data is available, for this research it is assumed that the vessel speed is normalized between these two values depending on the degree of loading.

In the rest of the section, more information is provided about the calculations concerning the power that is required by the propellers for horizontal power resistance of the vessel. When a ship generates a certain power within the Engine Room, this power will be transmitted along the propeller shaft and eventually to the tips of the propeller blades. There will be several losses of power between the Engine Room and the propeller tips. To calculate the power that is required from the main engine, efficiency between the various systems need to be taken into account. Taken the calculated total resistance into account, the naked effective power P_{NE} can be calculated accordingly Equation 3.25

$$P_{NE} = R_T \cdot V_s \qquad \text{(calm weather conditions)} \tag{3.25}$$

A common used parametric approach for the prediction of the ship resistance is the Guldhammer Harvald method, that was developed for calm water conditions and is shown in Eq. 3.26 Based on this the resistance and a given forward speed of the ship, the Effective Power P_E required for propulsion can be calculated.

$$R_{tot} = \frac{1}{2} C_T \, \rho \, S \, V_s^2 \tag{3.26}$$

where R is the total ship resistance, C_T is the coefficient of total hull resistance in calm water, ρ is the density of the sea water and V is the ship's speed. The total ship resistance coefficient can be either derived from model test and used for prediction, or it can be calculated related on ship geometry parameters and formula's.The total resistance consists of (1) frictional resistance, (2) Residual resistance, and (3) Air resistance and has been sub-divided into Equation 3.27 which is based on the Prediction Method of developed by Holtrop. His method is based on the regression analysis of random model experiments and full-scale data, available at the Netherlands Ship Model Basin (Holtrop & Mennen, 1982).

$$R_{tot} = R_F(1 + k_1) + R_{app} + R_W + R_B + R_{TR} + R_A \tag{3.27}$$

Where:

R_F	=	frictional resistance according to the ITTC-1957 friction formula	(N)
$1 + k_1$	=	form factor describing the viscous resistance of the hull form in relation to R_F	(-)
R_{APP}	=	resistance of appendages	(N)
R_W	=	wave-making and wave-breaking resistance	(N)
R_B	=	additional pressure resistance of bulbous bow	(N)
$R_T R$	=	additional pressure resistance of transom stern	(N)
R_A	=	model-ship correlation resistance	(N)

Since the power consumption can be heavily effected by the weather conditions, it is a common practice in to translate the calm water resistance into a more realistic sea state resistance. A rule of thumb that is often used in literature is to increase the naked effective (towing) power (with 10-30%) which results in the effective power.

$$P_E = P_{NE} \cdot (1.1 - 1.3) \qquad \text{(sea conditions)} \tag{3.28}$$

Hull efficiency

The thrust delivered by the propeller to the water can be calculated with the hull efficiency. The Hull efficiency η_H is defined as the ratio between the effective power and the thrust power which the propeller delivers to the water. Normally the efficiency is around 98-99% (C. B. Barrass, 2004b), but is expected to be known for the various equipment of Van Oord.

$$P_T = \frac{P_E}{\eta_H} \tag{3.29}$$

Propulsive efficiency
The power delivered by the propeller can be calculated with the propulsive efficiency. The propulsive efficiency η_D is equal to the ratio between the Thrust power and the propeller power. Normally the propulsive efficiency is between the 60-75% (C. B. Barrass, 2004b).

$$P_D = \frac{P_T}{\eta_B} \tag{3.30}$$

Shaft efficiency
The shaft efficiency η_S depends, i.a. on the alignment and lubrication of the shafts bearings and on the reduction of the gear installed. Shaft efficiency is equal to the ratio between the power P_D delivered to the propeller and the brake power P_B delivered by the main engine. Normally the shaft efficiency is between the 95-98% (C. B. Barrass, 2004b).

$$P_B = \frac{P_D}{\eta_S} \tag{3.31}$$

Engine efficiency
The relation between the power measured at the thrust block and the input power P_I gives the mechanical efficiency of the ship's engine. Normally engine efficiency for Diesel machinery is between the 87.5-92.5% (C. B. Barrass, 2004b).

$$P_I = \frac{P_B}{\eta_{en}} \tag{3.32}$$

Total efficiency

$$\eta_{tot} = \frac{P_E}{P_B} \tag{3.33}$$

Admiralty Coefficient
The Admiralty Coefficient can be used to determine the relation between power , speed and the displacement of a ship, and it can also be used to compare valued correlated with the power (e.g. hull resistance or fuel consumption (Górski, Abramowicz-Gerigk, & Burciu, 2013). The formula for the Admiralty Coefficient can seen in Equation 3.34.

$$A = \frac{V^3}{P} \tag{3.34}$$

Where:

A	=	the dimensionless Admiralty Coefficient	(-)
V	=	the ship speed	(m/s)
P	=	main engine power	(kW)

As indicated in the formula above, the speed of the ship is, with a third power, the dominant factor in the relation. Hence, speed reduction is the most common way to reduce fuel consumption. This relation does not include a number of adverse effects on the power consumption. These undesirable effects are:

- an increase of the rate of hull and propeller fouling,
- a decrease on the propeller efficiency due to operation under different conditions than assumed for the optimization of its design,
- prolongation of the voyage, i.e. the time the main systems of the ship are engaged,
- reduction of the efficiency of waste heat recovery systems and consequently higher fuel consumption by auxiliary engines.

This is integrated in the model as follows. Within Van Oord, data is available about the vessel's speed that the ship can achieve when making using of full power available. This data is available under loaded conditions and empty conditions. With this data, the Admiralty coefficient is used to calculate back what the requested power is at a certain vessel speed. All resistance are therefore implicitly included, and normal weather conditions are assumed. Since the vessel speed is normalized depending on the filling degree of the TSHD, the power requirement of the propulsion system is normalized between these two values as well.

3.3.4. Unloading

The user of the model is able to choose between the unloading methods dumping (D), pumping (P), and rainbowing (RB). In terms of calculations, a distinction is made between the first method and the last two methods. First dumping is discussed, afterwards pumping and rainbowing are discussed in this section.

The energy consumers that are assumed to operate during dumping are the jetpumps (to get the load of the TSHD in suspension again), the bow thrusters (for accurate positioning of the vessel), the propellers (during maneuvering), and the power required for the board net. Equation 3.35, shows the equation for the total energy consumption during the unloading *dumping* stage. The time required for the dumping stage is assumed to be fifteen minutes, see Equation 3.36. In the energy calculations for the dumping stage, all the power consumers are multiplied with factors (based on fuel logs) in order to determine the required power.

$$E_{dumping} = \sum_{i=0}^{n} t_{dumping} \cdot (P_{board\,net} + P_{bow\,thrusters} + P_{jet\,pumps}) \tag{3.35}$$

$$t_{dumping} = 900\ (sec) \tag{3.36}$$

The energy consumers that are assumed to be operating during pumping and rainbowing (RB) are the jetpumps (to get the load of the TSHD in suspension again), the bow thrusters (for accurate positioning of the vessel), the inboard dredge pumps, and the power required for the board net. Equation 3.37, shows the equation for the total energy consumption during the unloading *pumping and rainbowing* stage.

$$E_{unloading} = \sum_{i=0}^{n} t_{pumping/RB} \cdot (P_{board\,net} + P_{bow\,thrusters} + P_{jet\,pumps} + P_{inboard\,dredge\,pumps}) \tag{3.37}$$

The duration for this stage is calculated based on an unloading production that is assumed to be know, see Equation 3.38. Based on user experience, it is known what a each equipment can achieve for a discharge production.

$$t_{pumping/RB} = \frac{V_{insitu\,load}}{Q_{g\,unloading}} \tag{3.38}$$

From this specified discharge production rate, the pressure on the suction side and the discharge side of the pump can be calculated, together with the mixture flow and the mixture density. Based on these values, the required hydraulic power of the dredge pumps is calculated equitable to the formulas used during the unloading stage. With the efficiency curve of the pump, the shaft power is now calculated.
For the calculations it has been assumed that the inboard dredge pumps are connected in series, and positioned at the bottom of the equipment. There is a pipeline on the suction side also positioned at the bottom of the equipment, and one discharge pipeline. The length of the discharge pipeline is specified as an input parameter, with a short discharge pipeline corresponding to method *rainbowing* and a longer discharge pipeline with *pumping*. Adjustable valves are assumed over the entire length of the suction side with which the unloading production rate is regulated. It is assumed that the production enters the valves with an equal amount over the entire length of the suction pipeline. This implies that the speed of the mix, and the density of the mix, would increase linearly from the start of the suction pipeline to the pump. Since the precondition must be met that the speed of the mixture is at least above the critical speed of the material, in order to prevent sedimentation, this is implemented in the model by setting the velocity at the critical velocity at the beginning of the suction pipe, see Equation 3.39. The speed that the mixture has over de length of the suction pipeline is calculated with Equation 3.40. The density of the mixture is the density of the water at the beginning of the suction side, see Equation 3.41, since no material has yet been added to the pipeline. Over the length of the suction pipeline, the density is calculated with Equation 3.42.

$$v_s(0) = v_{crit} \tag{3.39}$$

$$v_s(x) = v_{crit} + \frac{Q_g(x)}{A_s} \tag{3.40}$$

$$\rho_m(0) = \rho_w \tag{3.41}$$

$$\rho_m(x) = \rho_w + \frac{Q_g(x)}{Q_{in} + Q_g(x)} \cdot (\rho_{TSHD} - \rho_w) \tag{3.42}$$

The total resistance can be calculated with formula 3.43. With the density and the velocity of the mixture varying over the length of the suction pipe, the resistance of the straight part and the resistance due to the increase in velocity head varies locally, see Equations 3.46 and 3.44 respectively. If $x = L_s$, the resistance at height of the pump is calculated. The resistance due to the inlet loss is calculated with Equation 3.45. Since it is assumed that the pump is at height of the suction tube, the resistance due to the lifted height is zero, see Equation 3.48. It is assumed that there are no non-straight parts in the suction pipe, therefore this resistance factor is also zero, see Equation 3.47

$$\Delta H = H_v + H_i + H_r + H_{ksi} + H_{lift} \tag{3.43}$$

Where:

$$H_v(x) = \frac{\left(v_{crit} + \frac{Q_g}{A_s}\right)^2}{2g} \cdot \frac{\rho_w + \frac{Q_g(x)}{Q_{in}+Q_g(x)} \cdot (\rho_{TSHD} - \rho_w)}{\rho_w} \tag{3.44}$$

$$H_i = \alpha \cdot \frac{\left(v_{crit} + \frac{Q_g}{A_s}\right)^2}{2g} \cdot \frac{\rho_m}{\rho_w} \tag{3.45}$$

$$H_r(x) = \frac{\lambda}{D_s} \cdot \int_0^x \left(\frac{v_s^2}{2g} \cdot \frac{\rho_m}{\rho_w}\right) dx \tag{3.46}$$

$$H_{ksi} = 0 \tag{3.47}$$

$$H_{lift} = 0 \tag{3.48}$$

3.4. Output data

This section elaborates on the output that the model generates and the possibilities of using this output to generate performance indicators on project level, or per dredging stage. With this output the user of the model is thus able to provide down-drilled analyses about dredging operations.

The output that the model is able to provide is listed in Table 3.7.

Table 3.7: Output

Output	
Project duration	[*hours*]
Project planning	gant chart
Energy consumed	[*kWh*]
Power consumption	[*kW*]
Fuel consumed	[*liter*]
Emitted CO_2	[*kg*]
Project costs	[€]

To compare work methods, performance indicators for the evaluation of project is developed. Because assessing a work method on a project level and quantify the reduction potential of a measure are two different things, two different approaches must be taken into account. First, a method for the assessment on a project level is provided, which is based on a general approach developed by the IMO. Second, a method to calculate the cost efficiency of reduction potential measure is presented. The IMO provided guidelines for users to assist in the process of establishing a mechanism to achieve the limitation or reduction of GHG emissions from ships in operation (IMO, 2009). In the guidelines, a concept of a KPI for the energy efficiency of a ship in oration is presented. The efficiency is expressed in the form of CO_2 emitted per unit of transport work. This method could be used as an objective, performance-based approach to monitoring the efficiency of a ship's operation. The method is presented for the whole maritime sector and is used as a starting point during this thesis. The purest form of the Energy Efficiency Operational Indicator (EEOI) of the IMO is defined as the ratio of the mass of CO_2 (M) emitted per unit of transport work. For this thesis, this expression is slightly adjusted, so it matches better to a dredging project. The adjusted expression for EEOI to evaluate dredging projects and compare different work methods in this thesis can be found in Equation 3.49. This method can either be used on a project level, but is also use full to asses per dredge stage.

$$\text{Average EEOI} = \frac{\sum_i \sum_j \left(FC_{ij} \cdot C_{Fj}\right)}{\sum_i \left(V_{situ}\right)} \tag{3.49}$$

Where:

FC_{ij}	=	the mass of consumed fuel type j at trip i	(kg)
C_{Fj}	=	the fuel mass to CO_2 conversion factor for fuel type j	(kg / kg)
V_{situ}	=	situ sand volume of a project that needs to be transported	(m^3)

The cost-effectiveness of the reduction potential of measures is assessed as well. For the assessment, a reference project is simulated. Based on the the emitted CO_2 and the project costs of this reference project, cost-efficiency of measures are defined. All the measures that can cause potential emission reduction are compared with this reference project. However, since the hypothesis tested in this research, is that reducing the emission performance of a project, will likely cost more, the effectiveness of the measures must be weighed against these costs. More about the reference project and the associated costs of vessel operations can be found in Chapter 5. In a TNO study, performed for the tender IKZ, this has proven to be a useful approach, that sector-wide is accepted. (Rijkswaterstaat, 2018). The formula for the reduction potential of each measure is presented in equation 3.50.

$$\text{Cost effectiveness} = \frac{\Delta CO_2}{\Delta \text{Project cost}} \tag{3.50}$$

Where:

ΔCO_2	=	the reduced CO_2 emission	(tonne)
$\Delta Projectcosts$	=	the additional project cost	(M €)

3.5. Conclusion

Based on the conducted literature study, the model objective and functional requirements are formulated. The objective of the model is to quantify the level of emission, the financial impact, and the project duration of dredging projects. The functional requirements of the model are to support the user in finding emission reduction measures, to support the user in decision making on a project level, and to provide down-drilled insight in KPIs per dredging stage.

The model concept that is chosen is the OpenCLSim available at the GitHub of the TU Delft Hydraulic Engineering department, which is based on DES and ABS. It is developed in a dedicated Simpy environment in Python. The reason for this concept is threefold. First, this package has already been tested and proved to be useful for the simulation of dredging projects within Van Oord. Secondly, it reduces the computational time when many work methods must be simulated. Finally, the functional requirements and characteristics of the dredging cycle meet the characteristics of DES and ABS.

The structure of the model can be sub-divided into *equipment*, *activities*, *sites*, and *costs*. Per stage of the dredging cycle the level of emissions is calculated, based on the calculated power requirement, which depends on operational parameters and TSHD characteristics. The power requirement is calculated per main energy consumer. The power requirement of the *propellers* and the *inboard dredge pump* is explicitly calculated based on the indicated operational parameters and TSHD characteristics. The power requirement of the other consumers (jet pumps, bow thrusters, board net) is calculated based on standardized input (Van Oord data) and the duration that the equipment is on site.

4

Model Validation

This Chapter is a continuation of Chapter 3 and answers the final part of the third sub-question of this research.

How to develop and validate a model to assess the CO_2 emissions performance and corresponding financial implication of a project strategy?

Thorough validation is required before using the model in practice. Three different validation strategies are used to validate the model. In the first stage, *unit test* simulations are used to validate the model's functionality, see sub-section 4.1. Unit testing is done to validate the model. The generated output is compared with the analytical solution of the tested function. Afterwards, model results are cross-referenced against outcomes of an indicative method provided by literature. The outcome of this validation step is listed in Sub-section 4.2. To conclude, the duration of the modelled discrete events of the dredging cycle and the calculated fuel consumption are compared against historical data generated by Automatic identification system (AIS) tracking data and fuel consumption data of Van Oord in Section 4.3.

4.1. Internal validation of individual model components

The different model components have been validated. The model components are sub-divided in the (un)loading production rate, the corresponding duration of the stages, the energy consumption, fuel consumption, CO_2 and project costs. All these components are tested in small steps (by varying a single parameter per simulation), and each small step is verified. This way of testing is called test-driven development, or TDD, in software engineering. TDD has proven to be a useful method that forces code developers to test all these small steps (Beck, 2003), (Truong, Amblard, Gaudou, & Blanc, 2014) and (Onggo, Indriany, & Gunal, 2014). Running all unit tests demonstrates that all components of the model work well individually.

A simulation of a simplified dredging project is set up to validate each model component. This basic project concerns a hopper operating between two sites. The simulation stops when all the material that needs to be dredged is moved from the dredging site to the placement site. The characteristics of the hopper and the projects sites are listed in Table 4.1. The values concern fictional numbers and therefore they do not refer to actual characteristics. These fictional numbers have been chosen, so that validating and analytical recalculating of the simulations is more straightforward and transparent to do. The most important parameters are listed in the table, and the rest of the parameters is found in the relevant validation notebook, see in Appendix B.1.

Table 4.1: Parameter values for internal validation of individual model components

Parameter	**Value**	**Unit**
Distance	3600	m
Vessel speed	1	m/s
Volume to be dredged	3600	m^3
Trail speed	1	m/s
Width draghead	1	m
Jet penetration depth	1	m
Unloading production	1	m^3/s
Capacity	3600	m^3
Loading rate	1	-
Standard power consumers	1000	kW
Factor power consumers	1	-
Overflow losses	0	-
Specific fuel consumption	1	l/kWh
CO_2 conversion factor	1	kg CO_2/l
Costs	1	€/h, €/l, €/kg CO_2
Hopper filling degree	1	%

Per event of the dredging cycle, internal validation tests are simulated. Validating the dredging event, both the duration and the dredging volume, requires changing the following parameters: the trail speed, the draghead width, and the depth of the jet penetration. Validating the sailing events is more straightforward: only the sailing speed and sailing distance are varied. The unloading phase is validated by varying the unloading production rate. Furthermore, the fuel consumption, the vessel costs, the density of the fuel, the hoppers capacity, the volume to be dredged, the filling degree, and the loading rate are varied. To further illustrate the internal validation step, the result of one of these tests is presented in the rest of this section. The results of the other tests can be found in Appendix B.1. In total, 36 tests were conducted.

To illustrate the functionality of the execution of the unit test, an example is presented below. The individual model component concerning the *trail speed* is further elaborated in this section. The corresponding functions where the trail speed is embedded, are tested. For a range of trail speeds the model is compared to the analytical results. The analytical calculation of the outcome is done by manually calculating the formulas included in the model. An example calculation is presented below. Sub-section 3.3.2 presents the implementation and explanation of the used formulas.

To calculate the duration of the dredging event, the jet production is calculated in the model beforehand. The equation that is used to calculate the jet production is shown in Equation 4.1. The jet production is analytically calculated to be 1 m^3 / s. An increasing trail speed will result in a decreasing duration of the first dredging event. The duration of the loading event is analytically calculated in Equation 4.2.

$$Q_{g\,jet} = w_{draghead} \cdot h_{jet\,penetration} \cdot v_{trail\,speed} \cdot nr_{suction\,pipes} = 1 \cdot 1 \cdot 0.5 \cdot 2 = 1\frac{m^3}{s} \tag{4.1}$$

$$t_{loading} = \frac{V_{hopper} \cdot filling\,degree}{Q_{g\,jet} \cdot \frac{sec}{hour}} = \frac{3600 \cdot 1.00}{1 \cdot 3600} = 1.0 hour \tag{4.2}$$

The model calculates the power requirement based on operational conditions. The power required multiplied with the duration results in energy consumption. The energy consumption is analytically calculated in Equation 4.3.

$$E_{loading} = P_{loading} \cdot t_{loading} = 3733 \cdot 1.0 = 3733 kWh \tag{4.3}$$

Furthermore, with specific fuel consumption, CO_2 conversion factor, and cost factor set at the value of 1, the amount of energy consumption, fuel consumption, emitted CO_2, and costs have the same value. It is tested whether these conditions hold. The number of cycles and the emitted CO_2 per cubic meter of sand is also validated and analytically calculated in Equation 4.4 and 4.5.

$$\text{number of cycles} = \frac{Volume}{Capacity \cdot filling\,degree} = \frac{3600}{3600 \cdot 1} = 1 \tag{4.4}$$

$$\text{Emitted } CO_2 = \frac{kg\,CO_2}{Volume} = \frac{3733}{3600} = 1.04\frac{kg\,CO_2}{m^3} \tag{4.5}$$

Table 4.2 present the results of the modelled unit tests and analytical calculated functions.

Table 4.2: Results internal validation test: trail speed

Component	Unit	Condition (m/s)	Model value	Analytical value	Succeeded unit test
Duration loading	hr	0.5; 1.0; 2	1.036; 0.508; 0.253	1.0; 0.5; 0.25	yes
Power loading	kW	0.5; 1.0; 2	3734; 3982; 4496	3734; 3982; 4496	yes
Energy loading	kWh	0.5; 1.0; 2	3867; 2022; 1137	3734; 1991; 1124	yes
Fuel loading	l	0.5; 1.0; 2	3867; 2022; 1137	3734; 1991; 1124	yes
Costs loading	€	0.5; 1.0; 2	3867; 2022; 1137	3734; 1991; 1124	yes
CO_2 loading	kg	0.5; 1.0; 2	3867; 2022; 1137	3734; 1991; 1124	yes
number of cycles	-	0.5; 1.0; 2	1; 1; 1	1; 1; 1	yes
kg CO_2 / m^3	-	0.5; 1.0; 2	1.07; 0.56; 0.32	1.07; 0.56; 0.32	yes

A small error in duration is notable, since the model takes the intersection point between the jet production and the vacuum production, and calculates the duration based on this production. It should be further investigated how to eliminate this error properly. Yet, the value that the model generates corresponds to the analytical values for all tests. For this reason, the unit tests are successfully executed. It has been demonstrated, for the trail speed parameter, that all elements of the model work well individually, it is assumed that the model as a whole also functions properly.

4.2. Validation: cross-referenced with CEDA's indicative method

The analytically determined amount of CO_2 can be different in practice. Therefore, an additional validation is conducted concerning the validation of the generated CO_2 footprint, the most important output that is generated by the model. Literature concerning the approach of validating this topic is scarce, mainly due to the confidentiality concerning fuel consumption. An indication on emissions during dredging operations is presented in the book "dredging for sustainable infrastructure" by Loboyrie et al. (2018). The book lists the emissions for several hopper sizes and placement strategies. Table 2.1 lists the results of the CO_2 footprint per case. Since the method does not specify all the information that is needed in order to simulate with the model, some assumptions about the operational conditions are taken into account:

- The maximum speed of the vessel is used based on ship data of Van Oord;
- The dredging depth of the dredge location is 24 meters;
- Two suction pipeswat b are considered, and only one discharge pipe;
- A diesel hybrid drive train is considered;
- Marine Diesel Oil is considered;
- No overflow losses are considered.

The several cases are simulated with the model, and the output is listed in Tables 4.3, 4.5, and 4.4. For the simulation, five different hopper split barges of Van Oord that suit the different categories are selected. Note that the numbers presented in Table 2.1 are based on maximum and minimum emissions within a statistical envelope of emission representing 85% of de Europe Dredging Associate (EuDA) fleet and the simulation results are only based on the input of the five different vessels.

Table 4.3: Validation discharge via bottom doors

TSHD size category	Reference cycle, discharge via bottom doors	Output model	Within benchmark
	(kg CO_2 /situ m3)	(kg CO_2 /situ m3)	(-)
<4,000 DWT	3.9 - 2.0	2.7	yes
4,000 <DWT <8,000	3.4 - 1.9	2.44	yes
8,000 <DWT <16,000	3.2 - 1.7	2.44	yes
16,000 <DWT <32,000	3.0 - 1.6	2.35	yes
32,000 <DWT	2.8 - 1.4	2.2	yes

Table 4.4: Validation discharge via rainbowing

TSHD size category	Reference cycle, discharge via rainbowing	Output model	Within benchmark
	(kg CO_2 /situ m3)	(kg CO_2 /situ m3)	(-)
<4,000 DWT	3.7 - 2.4	3.04	yes
4,000 <DWT <8,000	3.5 - 2.3	3.02	yes
8,000 <DWT <16,000	3.4 - 2.2	3.32	yes
16,000 <DWT <32,000	3.3 - 2.2	3.58	no
32,000 <DWT	3.2 - 2.1	4.16	no

Table 4.5: Validation discharge via pumping

TSHD size category	Reference cycle, discharge via pumping	Output model	Within benchmark
	(kg CO_2 /situ m3)	(kg CO_2 /situ m3)	(-)
<4,000 DWT	4.0 - 2.5	3.83	yes
4,000 <DWT <8,000	3.6 - 2.4	3.76	no
8,000 <DWT <16,000	3.5 - 2.3	3.87	no
16,000 <DWT <32,000	3.4 - 2.2	4.02	no
32,000 <DWT	3.2 - 2.1	4.56	no

The results show that the values that the model generates fall partly within the benchmarks of the fleet. The method of dumping via bottom doors is completely validated. The method of dumping via the pumping system, and via rainbowing, is partly validated. It is not fully clear what the calculations of the CEDA method are based on, and further explanation is needed to explain this difference. In the calculations with the model, it is assumed that all ships use the fuel type MDO. Cleaner fuels (i.e. HFO, bio fuels) are also used in the dredging industry, and this can lead to a difference. The calculations of the model also assume a standard pipeline configuration, which may differ from ship to ship and result in the difference in output.

4.3. Validation base case project

In this section, the comparison of the generated output of the model is compared to historical data. This is done to be able to validate the output generated by the model. It also generates insight into whether the model results are a good indication for actual projects. For this comparison data from a historical Van Oord case is compared to the model output generated with project-specific input. It is evaluated to what extent the model matches reality to see if real-world model applications are possible in the near future.

The validation case concerns a Dutch nourishment project for the coastline preservation, located near Texel. The total volume to be dredged is 1.150.000 m^3 in-situ coarse sand. The material to be dredged is coarse (d_{mf} = 277 μ), overflow losses are assumed. The remaining project parameters are found in the Appendix B.2. This project is also chosen as the base case project. All measures to reduce CO_2 are compared to the results of this base case. The reason that this project is chosen as the base case project is twofold. First, the logistics of the project are not complicated. The project is executed with a single hopper, and the path that the vessel sailed was constant during the operations. Second, during the project, there was no downtime due to a technical malfunction, and the weather conditions were relatively mild. These conditions are favourable because this matches how the model simulates a project the most closely relative to other projects. The generated output of the model is elaborately discussed in Chapter 5, the main results, the ones important for this part of the validation are presented later in this section.

AIS is an automatic tracking system that uses transponders on ships and is used by vessel traffic services. This data can be translated into the exact path that a vessel has sailed. By indicating the dredging and placement location on the map, the duration of the different dredging events can be distilled from the data per event. This approach also calculates the number of trips. On top of this AIS data, the summarized fuel consumption logs are used.

The generated model output together with the historical data per event is presented in Figure 4.1. The graph presents the duration per event per cycle, with a dot. The dotted lines, represent the model output per cycle, per event, calculated by the model. First, the spread of the historical data will be discussed further, after which the difference between the historical data is compared with the generated cycle times from the model.

The deviation of the historical duration per event varies per event-type. Note that the model does not include external influences, such as weather conditions, and irregularities in the soil profile. It is likely that the external effects cause the historical data to have a high variance as compared to the model output. The largest deviation can be seen during the pumping and loading stages of the project, less deviation is detected during the sailing stages. It is understandable that the activities dredging and pumping consist of more deviation than the sailing activities if the complexity of the activities is analysed. The extraction depth, the soil properties and consistency of the bed level influence the dredging process, and change per excavation location. The soil properties influence the settling process in the hopper basin and are also an essential factor for the sedimentation process in the pipeline. Due to all these dependencies on the duration of the loading and pumping process, it can indeed be explained that there is a more significant deviation. Over the entire project, the path that has been sailed has remained constant and the weather conditions were mild. It is likely that due to these influences, the spread of the various sailing activities is small. After a hundred cycles, a reduction can be seen in the duration of the sailing activities. This could identify a point in time where the weather conditions have changed.

The comparison of historical data with the model results is summarised in Table 4.7 and the results are further discussed per event. The calculated loading duration, see Equation 4.4, is determined by the width of the draghead, the trail speed, the depth of the jet penetration, and the number of suction pipes operating. Assumed that the width of the jets and the number of operating suction pipes do not vary during operations, then the explanation for this difference should be in the trail (v_{trail} = 1 m/s in this simulation) speed or the penetration depth (h_{jet} = 0.25 m). It is possible that due to mild weather conditions and therefore a relatively lower resistance while sailing, the ship was able trail faster than normal. It could also be that the ground was less firmly packed and the jets could penetrate deeper. It could also be that the material was a lot less coarse than expected and that the assumption that everything was settled right away was not correct. In that case, the loading phase lasts longer because the maximum production in terms of the load is only reached later due to the overflow losses. The duration of unloading differs only 3% the model results. The calculated duration of the sailing events is based on a fixed distance from a point to point. The actual distance travelled per cycle will not have exactly the same distance, so the duration of this event can also vary. Furthermore, the model assumes that the ship is sailing at 90% of the maximum speed. It may be that the actual speed achieved is slightly higher.If the average cycle times are considered, this deviates very little from the model calculations, namely 1.4% and 1.5% or sailing empty and sailing full correspondingly. The number of trips that are calculated by the model only differ with one trip from the actual operations, which results in a deviation of 0.54 %. The total project duration is calculated to be 33.2 days. The actual project duration is 35.18 days. The difference between these values is partly explained by the underestimation of the loading phase and probably due to the simplified cycle in the model since fuelling and downtime are not included. Fuel logs per step are not available for this research. The data that is collected, concerns the total fuel consumption of one production week during the execution of this project. This data is used to make an estimation for the entire project. Although the cycle duration only has an accuracy of 6.17%, the fuel consumption per operational hour has an accuracy of 1.29 %.

Figure 4.1: Validation base case project time spend per event *Axes left out due to confidentiality

Table 4.6: Comparison model results with historical data

Parameter	Unit	Model	historical	Deviation (%)
Duration per trip loading	hours	1.31	1.37	3.96
Duration per trip unloading	hours	1.99	1.93	3.00
Duration per trip sailing empty	hours	0.5	0.49	1.44
Duration per trip sailing full	hours	0.48	0.47	1.50
Cycle duration	hours	4.31	4.59	6.17
Total project duration	days	33.2	35.18	5.96
Number of cycles	-	185	184	0.54
Averaged fuel consumption	liter / operational hour	*	*	5.08
Total fuel consumption	M liters	*	*	1.29
Emitted CO_2	kg / m^3	*	*	1.05

* Left out (confidential)

NOT CONFIDENTIAL

Table 4.7: Comparison model results with historical data

Parameter	Unit	DT Model	historical	Deviation (%)
Duration per trip loading	hours	1.31	1.37	3.96
Duration per trip unloading	hours	1.99	1.93	3.00
Duration per trip sailing empty	hours	0.5	0.49	1.44
Duration per trip sailing full	hours	0.48	0.47	1.50
Cycle duration	hours	4.31	4.59	6.17
Total project duration	days	33.2	35.18	5.96
Number of cycles	-	185	184	0.54
Averaged fuel consumption	liter / operational hour	1923	1830	5.08
Total fuel consumption	M liters	1.53	1.55 [a]	1.29
Emitted CO_2	kg / m^3	4.70	4.75[b]	1.05

[a] Fuel consumption per operational hour averaged out over entire project.
[b] Based on fuel consumption and carbon content per fuel.

4.4. Conclusion

The model's internal components are successfully validated. The level of emitted CO_2 falls (partly) within the benchmarks of the indicative method presented by the CEDA. A case study is simulated, and the results are compared with historical data. For this stage of the development, the model's output is assumed acceptable as most of the output of the model fall within a range of <5%. The fuel consumption is and the project duration fall without this range, it must be further investigated why this is due. In any case, in this development stage the model can already act as a proof of concept.

5

Application and Results

This chapter answers the fourth and the fifth sub-question of this research:

What are the quantitative contributions of different factors that influence the CO_2 emissions at project level, and what is the corresponding financial implication of these factors?

What part of the desired emission reduction can be achieved by optimising project strategies?

Now that the model has been validated, it is time to put the model into operation. The content of this chapter shows how the different facets of the model work, and demonstrate how a work method can be found with minimal emitted CO_2. To provide a frame of reference for the different work methods tested, a basic project is simulated. The settings of this project, reflect the execution of a project as it is performed during conventional standards: a project where costs per dredged cubic meter are optimised. In the rest of this chapter, this project is referred to as the base case scenario.The base case project and the output of the model are presented in Section 5.1.

Subsequently, after the presentation of the base case results, the optimisation possibilities found by using the model are elaborated per category. The operational aspects (determined by the work method strategy of the contractor) are discussed in Section 5.2. Furthermore, the policy measures are discussed in Section 5.3. Afterwards a conclusion is formulated to answer the fourth and the fifth sub-question in Section 5.4.

5.1. Base case project

To demonstrate the output that the model and to provide a reference for the presented measures, a simulation was run of a chosen base case project. The base case project that is chosen, concerns a Dutch sand nourishment project for the coastline preservation. In the next sections, different factors are tested, to find optimisation possibilities. The reduction potential of the proposed measures can be compared with reference to this project to formulate a final conclusion and recommendation as discussed later in this chapter.

The project is executed by a single TSHD. There was only one hopper operating between the dredge location and the dump location. In Table 5.1 a summary of the characteristics of the sites and the equipment is found. The data about the power requirement per event per main consumer, and the corresponding load factors are, for confidentiality reasons, not listed in this table.

Table 5.1: Input parameters for the simulation of the base case with the model; partly presented due to confidentiality

Parameter	**Value**		**Note**
Type of equipment	TSHD	(-)	
In situ material to be dredged	1,150,000	(m^3)	
Fuel type	MDO	(-)	
Total installed power	12,000	(kW)	
Power requirement per event per main consumer	-	(-)	confidential
Load factor per event per main consumer	-	(-)	confidential
Extraction depth	24	(m)	
Sailing distance	13	(km)	
Sailing speed (loaded)	15.0	(knots)	
Sailing speed (empty)	15.5	(knots)	
SFC	0.2	(l/kWh)	
(un)loading production rate	0.9	(m^3/s)	
Length of discharge pipe	2000	(m)	
Hopper capacity	6473	(m^3)	
Overflow losses	0	(-)	

The total energy that is consumed, is calculated to be 7,079,132 kWh over a period of 30 days. In Figure 5.1, this energy consumption is shown, divided per dredging event. It can be shown that, due to a combination of duration per event and power requirement, the unloading phase is the stage where the largest amount of energy is consumed. This can partly be explained by the large pumping distance.

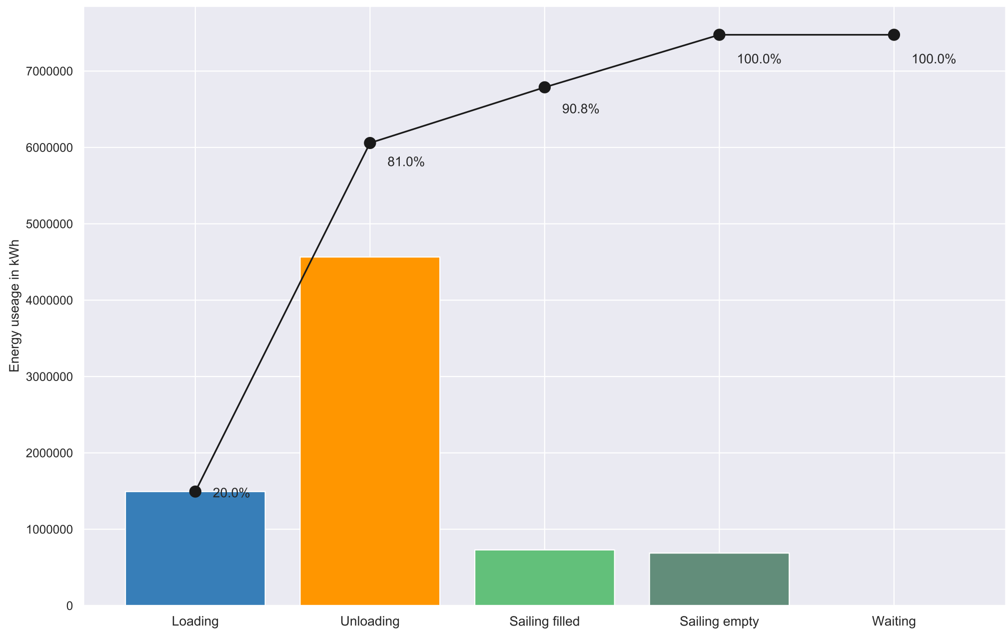

Figure 5.1: Energy consumption in kWh per cycle event for the base case simulation: a single TSHD performing a beach nourishment making use of *pumping* as unloading method

Since the amount of fuel that is used and the amount of emitted CO_2 are directly related to the amount of energy that is required, the plots clearly show the same ratio. The results are shown in the Figures 5.2 and 5.3 respectively. The user is presented a Gantt chart in which individual events are identified, and the whole project planning can be seen.

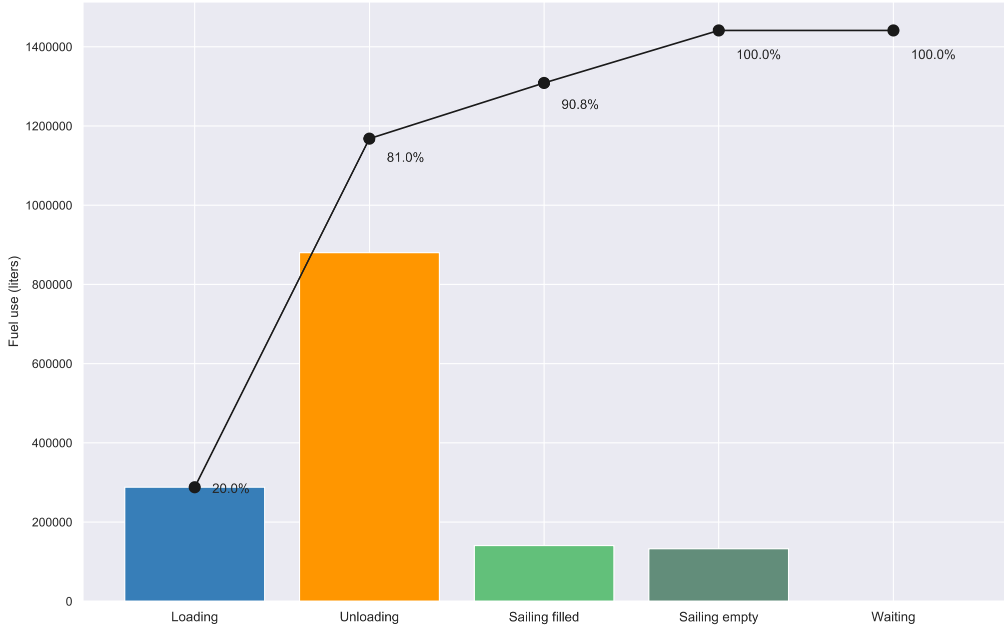

Figure 5.2: Fuel consumed in liters MDO per cycle event for the base case simulation: a single TSHD performing a beach nourishment making use of *pumping* as unloading method

To conclude, all the important data retrieved from running the simulation of the reference project is summarized in Table 5.2. This data functions as a baseline project, and the output of the simulations for alternative work methods can be compared with this data.

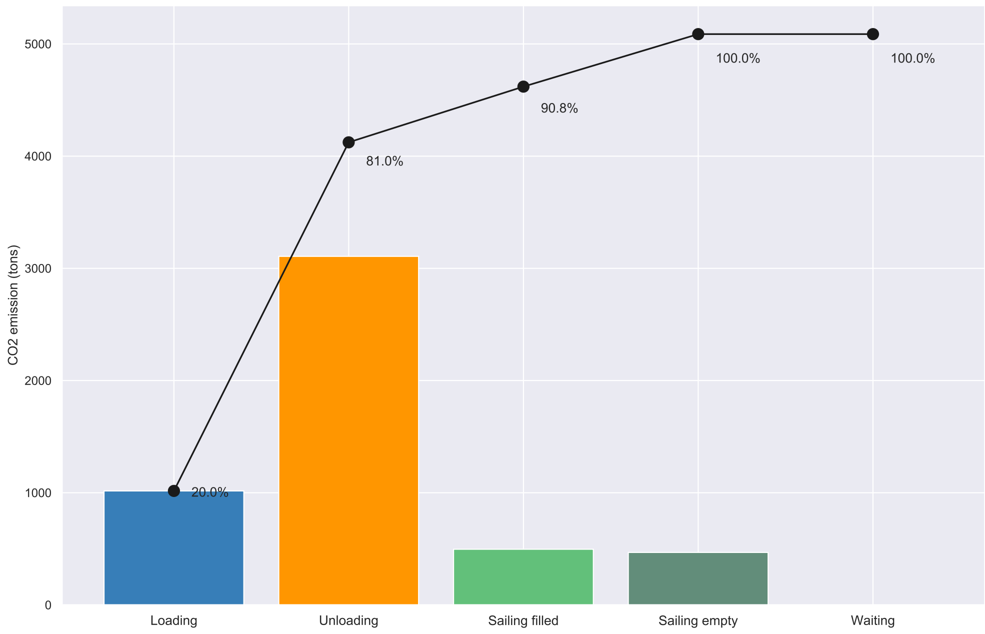

Figure 5.3: Emitted CO_2 per cycle event for the base case simulation: a single TSHD performing a beach nourishment making use of *pumping* as unloading method

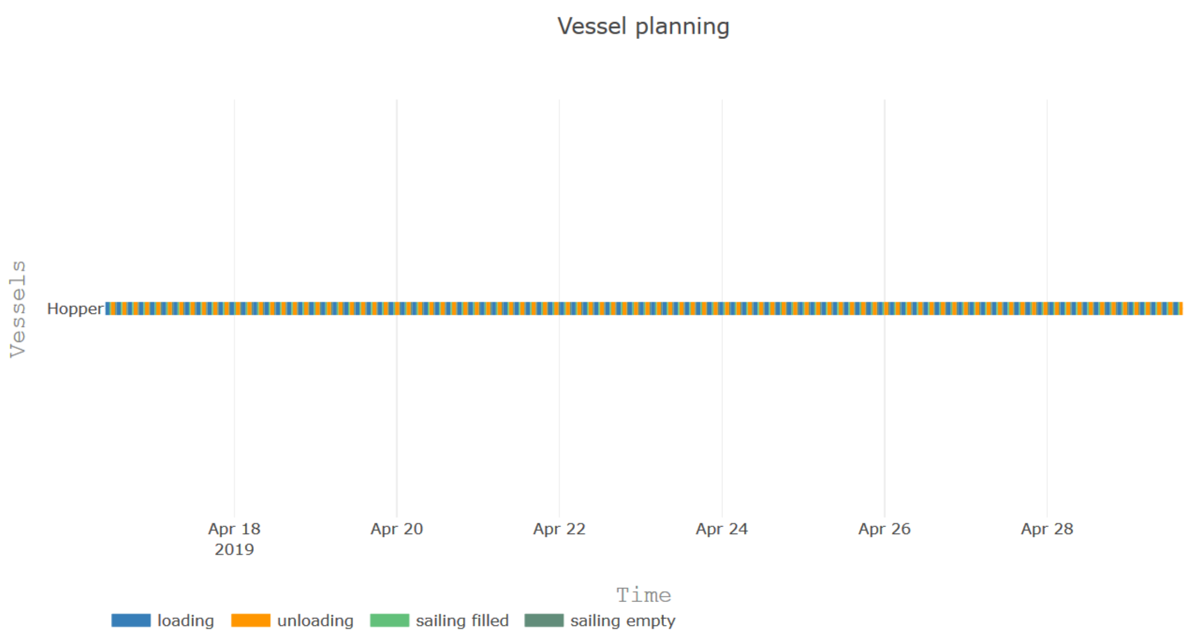

Figure 5.4: Project planning presented in a Gantt chart for the base case simulation: a single TSHD performing a beach nourishment making use of *pumping* as unloading method

Table 5.2: Generated model output for the base case project; presenting key performance indicators regarding energy consumption, fuel consumption, and CO_2 emissions for the total project and per cycle event

Parameter	Value	Note
Total energy consumed	7,079,132	(kWh)
Energy consumed loading	1,434,223	(kWh)
Energy consumed sailing filled	729,412	(kWh)
Energy consumed unloading	4,227,816	(kWh)
Energy consumed sailing empty	687,680	(kWh)
Total fuel consumed	1,364,857	(l)
Fuel consumed loading	276,518	(l)
Fuel consumed sailing filled	140,630	(l)
Fuel consumed unloading	132,584	(l)
Fuel consumed sailing empty	815,122	(l)
Total emitted CO_2	4818	(tons)
Emitted CO_2 loading	976	(tons)
Emitted CO_2 sailing filled	496	(tons)
Emitted CO_2 unloading	2877	(tons)
Emitted CO_2 sailing empty	468	(tons)
Total Emission performance Indicator	4.19	(kg CO_2/m^3)
Emission performance Indicator loading	0.85	(kg CO_2/m^3)
Emission performance Indicator sailing filled	0.43	(kg CO_2/m^3)
Emission performance Indicator unloading	2.50	(kg CO_2/m^3)
Emission performance Indicator sailing empty	0.41	(kg CO_2/m^3)

5.2. Optimisation of operational aspects

The examined operational aspects on the influence of the CO_2 emissions are the vessel speed, the trail speed, the unloading production, the type of vessel, and the fuel used. These parameters are discussed in the corresponding sub-sections.

5.2.1. Vessel speed reduction

During the sailing stages of the dredging cycle, the propellers of the hopper are the biggest energy consumers. For that reason, the first measure that is investigated concerns this energy consumer. In current practice, a vessel is always operating at highest possible vessel speed. In this case, the project is executed with shortest project duration. With the current fuel prices, the costs for the vessel being on site are still normative.

Speed reduction as an operational measure, is a widely discussed measure in the transportation world, the literature on this specific topic in the dredging industry is scarce, this is mainly due to the confidentiality of the fuel information. Although this topic has been widely discussed as being an effective measure, at project level in the dredging industry it has never been analysed how much CO_2 can actually be reduced. Due to the cubic relation between the specific fuel consumption and the speed of the vessel, it is very clear that a vessel that sails faster consumes disproportional more than the same vessel that sails slower. It can be concluded that, the effect of adapting the vessel speed of the vessel to both operating costs and emissions is considerable (C. Kontovas, Psaraftis, & N., 2011). For the calculation model, it is assumed that the specific fuel consumption is a cubic function of the vessel speed and a function of the total payload. This can be seen as an realistic closed-form approximation (C. B. Barrass, 2004a). In reality, the fuel consumption depends on more parameters. In the simulations, calm weather conditions are assumed. The weather conditions can in reality, for example, cause on additional increase of 15% - 30% of the total fuel consumption (MAN Diesel & Turbo, 2013). Also the conditions of the hull of the vessel plays an important role, which is assumed to be in clean conditions in this simulation. All the input and detailed information, as well as the script of the simulation can be found in Appendix D.

The effect of reducing vessel speed is only reflected in the sailing phases of the project. Figure 5.5 shows the relation between speed and required power, time and energy consumption on the propellers. The graph shows the consumption for a single trip from winning location to dump location. The resistance that the vessel encounters on the propeller depends on whether the vessel is loaded or not. The figure shows that the vessel achieves a higher maximum speed when the vessel is in unloaded condition.

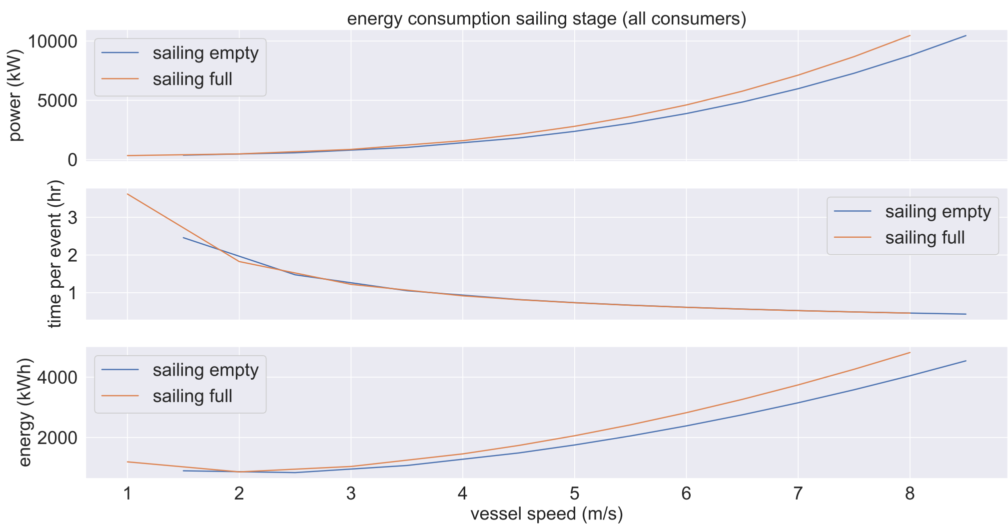

Figure 5.5: Consequences of *vessel speed* (m/s) optimisation in terms of power requirement (kW), duration (h), and energy consumption (kWh) *per sailing event*

To see the effect of this at project level, Figure 5.6 presents the outcome of the simulation for all cycles. This therefore shows the consumption of both loading, unloading and sailing stages, but added together. Now it can be made clear how much energy can be saved at project level, and it can be calculated how much CO_2 this ultimately saves. In the graph the setting for the base case is indicated (sailing as fast as possible), together with the setting where the energy consumption is minimal, see the points on the energy graph. An optimum can be found in terms of energy consumption at a vessel speed of 2.5 m/s. The graph indicates, departing from the right, that it is visible that with a decrease of vessel speed the emitted CO_2 decreases until the tipping point of 2.5 m/s is reached. After this point, the extra time that is needed to execute the project is disproportional to the reduction of required power that is achieved with lowering the vessel speed.

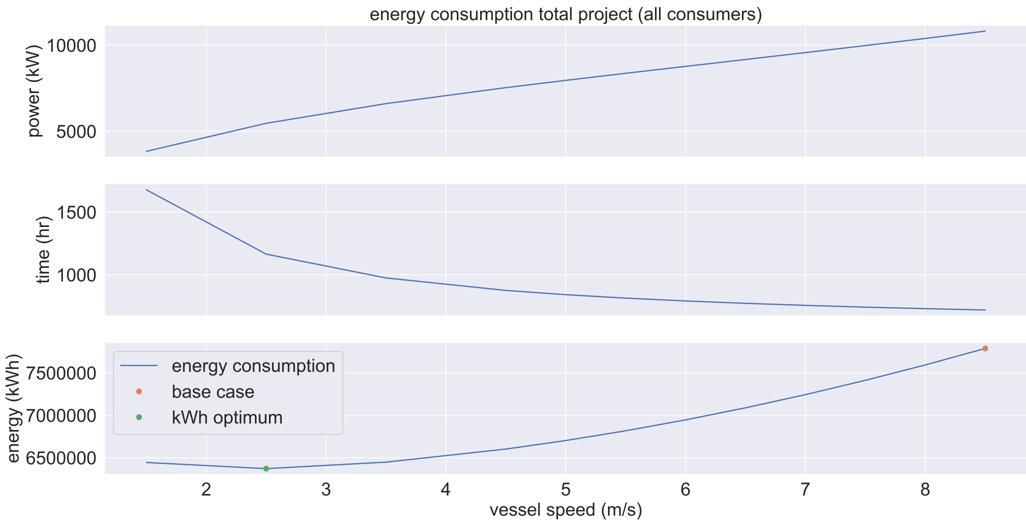

Figure 5.6: Consequences of *vessel speed* (m/s) optimisation in terms of power requirement (kW), duration (h), and energy consumption (kWh) on a *project level*; presenting the work point for the base case and the optimal work point in terms of kWh

The big question remains, how much CO_2 reduction is possible on a coastline project if a contractor would choose to operate at a lower vessel speed, and what is the corresponding financial impact for the contractor? To illustrate the answer to this question, the CO_2 emission per vessel speed is shown in Figure 5.7 and the project costs are shown in Figure 5.8. In the graph where the CO_2 emission is plotted against the vessel speed, the emitted CO_2 is subdivided per cycle event. It is shown that reduction in CO_2 emission is only reached when analysing the sailing stages. Since no other parameters are varied in this simulation, the total amount of emission stays constant during the (un)loading stages.

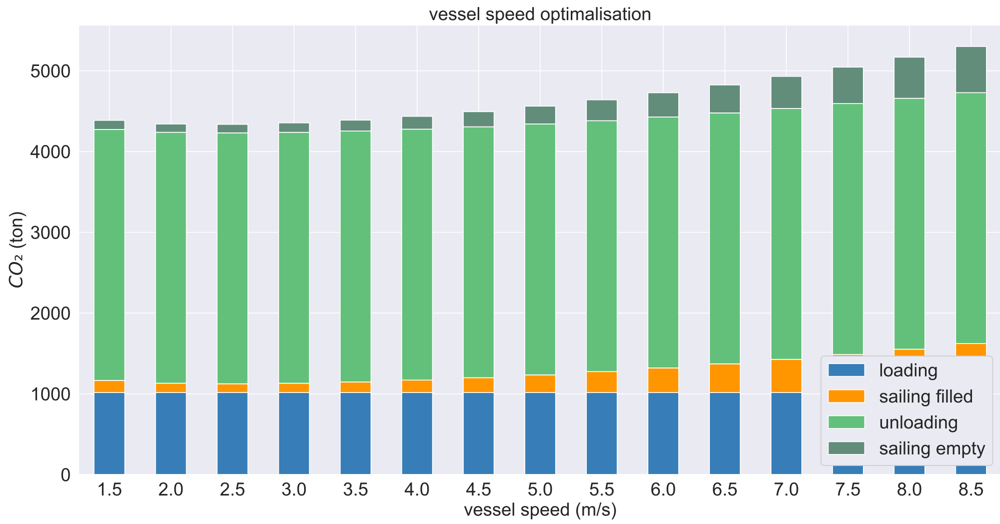

Figure 5.7: Consequences of *vessel speed* (m/s) optimisation in terms of emitted CO_2 on a *project level*, presenting the emissions per cycle event; the optimal work method with a vessel speed of 2.5 m/s is found

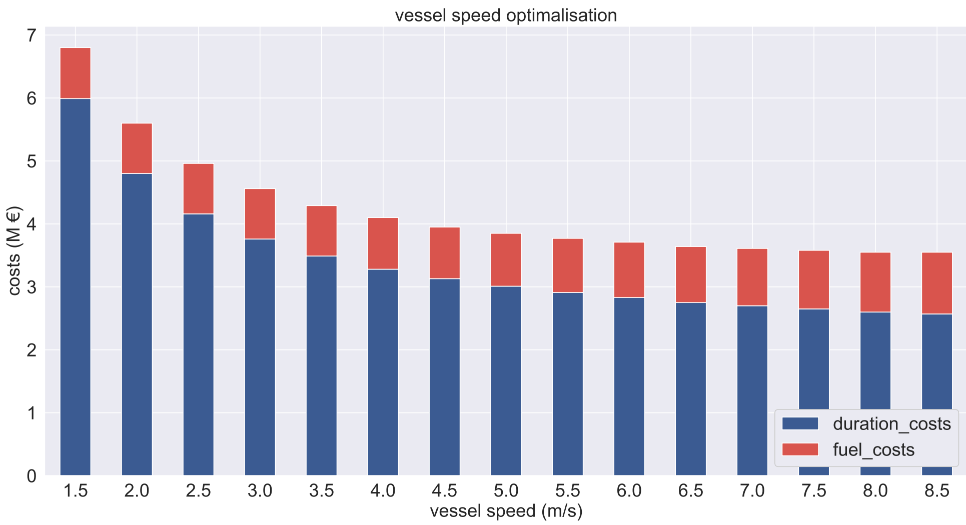

Figure 5.8: Consequences of *vessel speed* (m/s) optimisation in terms of project costs on a *project level*, presenting the costs divided in costs for the equipment being on site and in fuel and lubricants costs

It can be concluded that reducing the vessel speed is a very effective operational measure to decrease the CO_2 emission. In Table 5.3 the results are summarised. The work method according to standard procedures (base case) is compared with the optimal work method in terms of emitted CO_2, to show the reduction potential of the measure in the extreme case. Therefore it is interesting to compare this strategy with the most optimal strategy in terms of emitted CO_2. It can be concluded that the sailing distance has a significant role. Furthermore, it can be seen that an optimisation on CO_2 emissions results in a different strategy for the dredging project than with optimising on project time and on project costs.

Table 5.3: Comparison of the *base case* work method with the CO_2 *optimisation* work method for *vessel speed* optimisation; model output presented in terms of emitted CO_2 (tons), project duration (days), and project costs (M €)

Work method	**Vessel speed**	CO_2 **(tons)**	**Duration (days)**	**Costs (M euros)**
Base case	8.5	5096	30.75	3.57
Minimal CO_2	2.5	4337	49	4.96
	Difference	759 (- 14.9 %)	18.25 (+59.3 %)	1.39 (+38.9 %)

5.2.2. Trail speed optimisation

The next parameter that is examined is the trail speed during dredging. During conventional operations, the vessel is operating with the highest possible trail speed. Based on experience, this trail speed appears to be around 1 m/s. When simulating the base case, this value was therefore also assumed.

To properly understand the effect of adjusting the trail speed, this is explained in the following three steps. The effect of adjusting the trail speed has a direct influence on the production and the associated hydraulic transport, and it also has an effect on the sailing resistance that the vessel experiences. Because it concerns the production, adjusting the trail speed also indirectly affects the duration of the event loading. The effects are further explained below.

First the effect of trail speed on production and hydraulic transport is explained. The head of the pump is determined by the total manometric head. This consists of the pipeline resistance and the vacuum that the pump must deliver. The upper limit of the vacuum is the maximum vacuum. With a reduction in the trail speed (and therefore production), the required vacuum drops to pump the production that belongs to that trail speed. This therefore has a favourable effect on energy consumption. On the other hand, when you reduce the trail speed, the time required to fill your hopper increases since the production is lowered. It is therefore to be expected that an optimum can be found concerning the energy consumption of the inboard dredgepumps. In Figure 5.9 the required shaft power, the duration to load the hopper, and the energy consumption is plotted. It is showed that an optimum has indeed been found. It is shown that the point at which the energy consumption is at this minimum is not the same point for which the duration is shortest. It can be concluded that reducing the trail speed during loading, indeed results in reducing the CO_2 emission when only the dredgepumps are concerned.

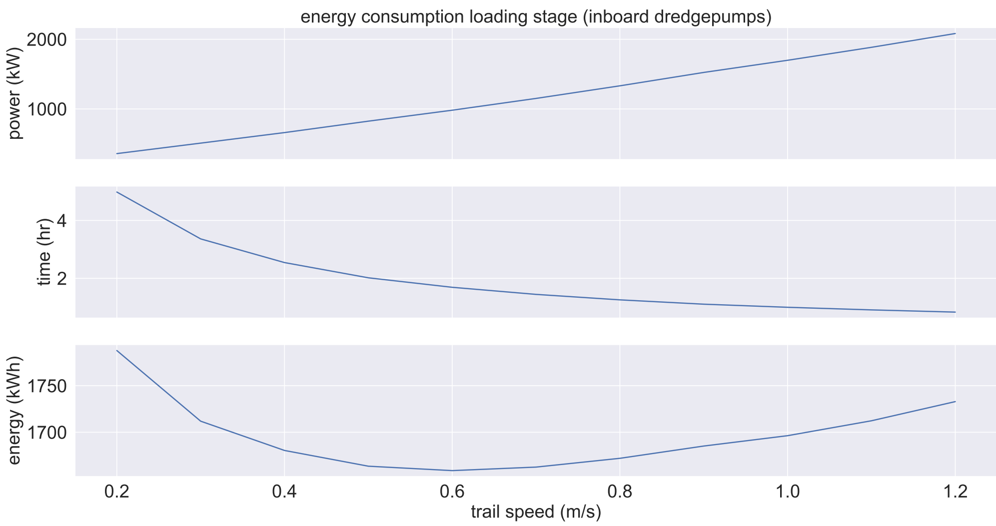

Figure 5.9: Consequences of *trail speed* (m/s) optimisation on the inboard dredgepumps in terms of power requirement (kW), duration (h), and energy consumption (kWh) for the *loading event*

Although optimization can be made in terms of CO_2 with regard to the dredge pumps, this does not mean that it is possible at project level to optimise on these parameters. During the pumping, there are more energy consumers on than just the inboard dredge pumps. The jet pumps and the board network also use energy. The model also assumes a fixed value for the energy that the propellers need to absorb the extra resistance that the vessel undergoes as a result of towing. Because these energy consumers are also included, the optimization effect of the inboard dredge pumps is lost. The extra time required when lowering the trail speed has a greater effect on the total energy consumption than reducing the energy consumption to lower the trail speed. Figure 5.10 presents the total power requirement, project duration, and energy consumption at a project level.

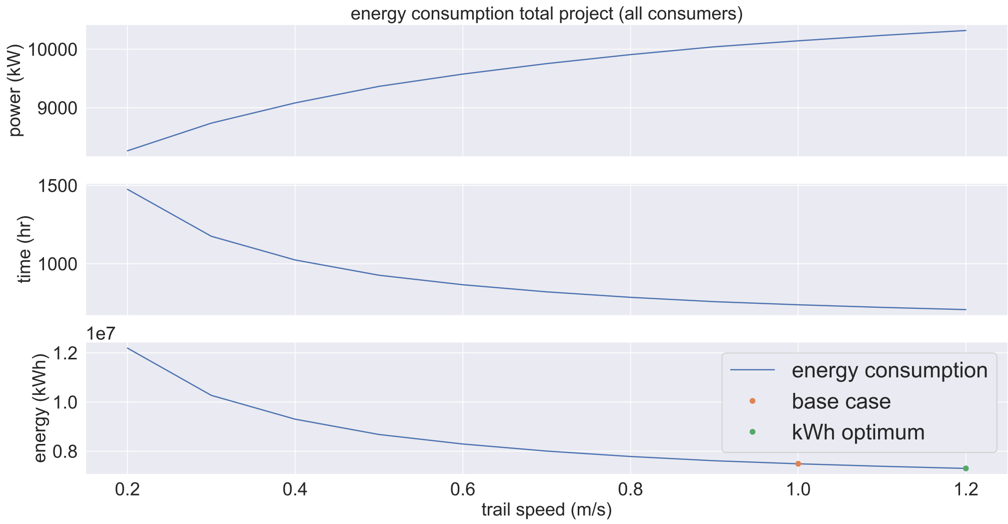

Figure 5.10: Consequences of *trail speed* (m/s) optimisation on in terms of power requirement (kW), duration (h), and energy consumption (kWh) for the *total project*; presenting the work point for the base case and the optimal work point in terms of kWh

It can be concluded that, with these operational setttings and vessel characteristics, the most optimal trail speed, is as fast as possible. The trail speed that can be reached is limited by the available power or the vacuum, and is 1.2 m/s within this project. A small reduction in emitted CO_2 can be achieved. In Figure 5.11 the emitted CO_2 is plotted per trail speed, and in Figure 5.12 the project costs are plotted. In Table 5.4 the results of this optimisation are shown. The figures show that it is in the interest of the contractor to trail as fast as possible regarding CO_2 reduction, minimisation of project duration and project costs. Minimizing on CO_2 and costs yields the same strategy for a dredging contractor, as opposed to sailing speed reduction as explained in Sub-section 5.2.1.

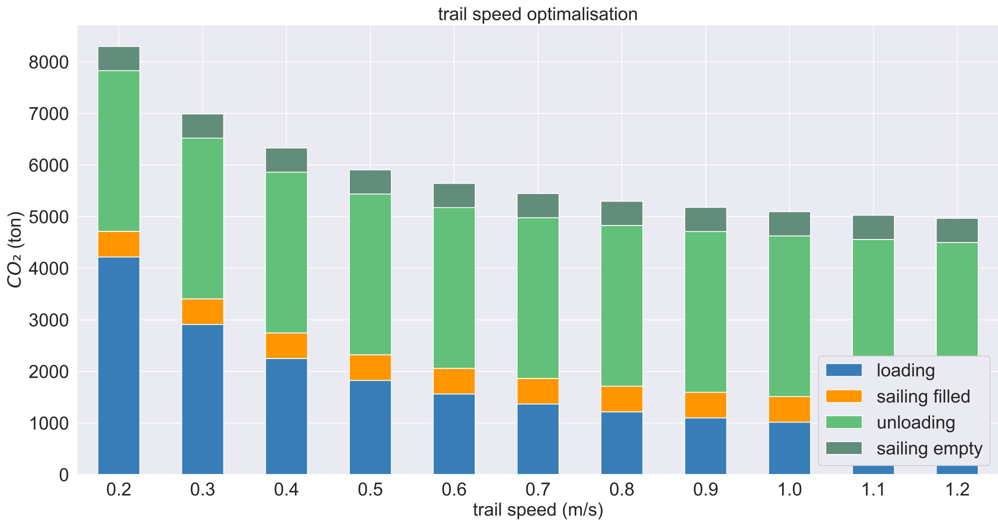

Figure 5.11: Consequences of *trail speed* (m/s) optimisation in terms of emitted CO_2 on a *project level*, presenting the emissions per cycle event; the optimal work method concerns trailing as past as possible

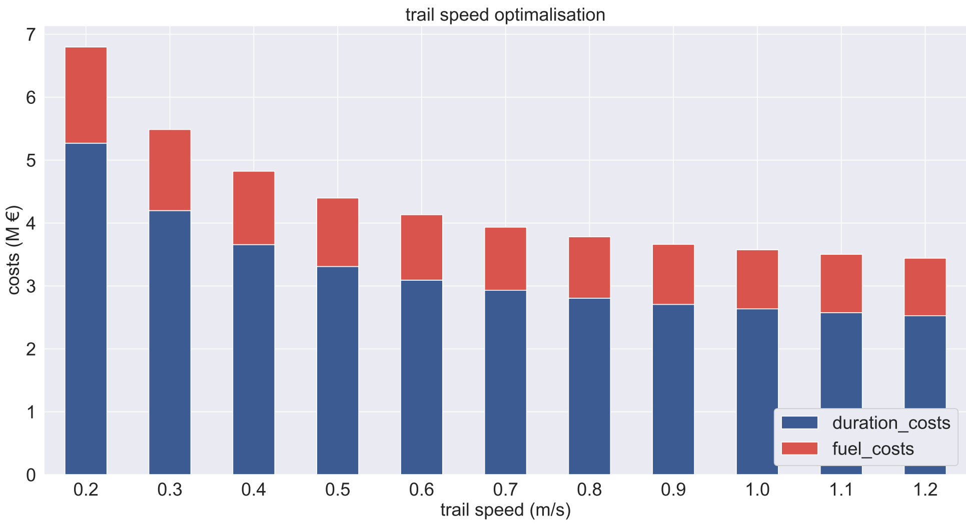

Figure 5.12: Consequences of *trail speed* (m/s) optimisation in terms of project costs on a *project level*, presenting the costs divided in costs for the equipment being on site and in fuel and lubricants costs

Table 5.4: Comparison of the *base case* work method with the CO_2 *optimisation* work method for *trail speed* optimisation; model output presented in terms of emitted CO_2 (tons), project duration (days), and project costs (M€)

Work method	**Vessel speed**	**CO_2 (tons)**	**Duration (days)**	**Costs (M euros)**
Base case	1.0	5096	30.75	3.57
Minimal CO_2	1.2	4968	29.5	3.44
	Difference	128 (- 2.5 %)	1.25 (-4.2 %)	0.13 (-3.74 %)

5.2.3. Unloading production

The next factor discussed in this section is the influence of discharge production on energy consumption and CO_2 emissions. For this reason, it is assumed that the amount of production that ends up in the pipeline system is controllable, by opening valves on the pipeline.

Chapter 3 explains in detail how the model, with the adjustable production as input parameter, calculates the manometric head. This head must be delivered by the pumps. The unloading production that is used in the base case, is calculated on the basis of user experience: an average production rate that belongs to this vessel. In the case of the vessel tested, this is a production of 0.9 m^3/s. The calculated head for the base case is higher than the installed capacity of the inboard dredge pumps, which is partly explained due to the large length of the discharge pipeline (= 2000 m). It is assumed that this extra head is delivered by booster pumps with the same efficiency. For this example, it is also assumed that the manometric head that exceeds the capacity of the pumps is delivered by booster pumps. In addition to the effect on the energy consumption, production also has an effect on the time of the unloading event. It is to be expected that an optimum can be found for where the production is pumped the most energy efficiently, and where therefore the least CO_2 is emitted.

The results of the simulation indicate that an optimum can indeed be found. Adjusting the unloading production initially has an effect on the inboard dredge pumps during discharging, but also an indirect effect on the rest of the energy consumers because of the duration of the event. The effect on the inboard dredge pumps can be seen in Figure 5.13. It is clearly visible how, with an increase in production, more power is required from the pumping system. The time required to empty the hopper decreases with an increase in production. There is a minimum in energy consumption.

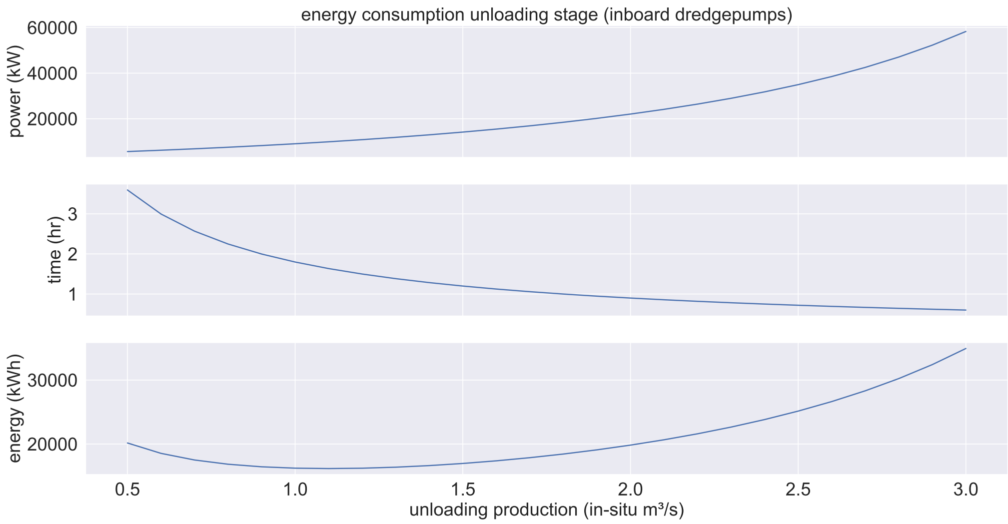

Figure 5.13: Consequences of *unloading production* (in-situ m^3/s) optimisation on the inboard dredgepumps in terms of power requirement (kW), duration (h), and energy consumption (kWh) for the *unloading event*

Figure 5.14 shows the effect of production for the entire project. All energy consumers are included in the calculations. The point of minimal energy consumption shifts to a higher production if all energy consumers are included. This can be explained by the fact that the effect of time makes a relatively greater impact than the effect of energy consumption on the in-dredge pumps. The graph shows the energy consumption for the base case, but also the minimum found. Therefore additional booster pumps are needed for this. However, the speed in the discharge pipelines increases when production is increased. It should be further investigated what the consequences are for the wear and tear of the pipelines.

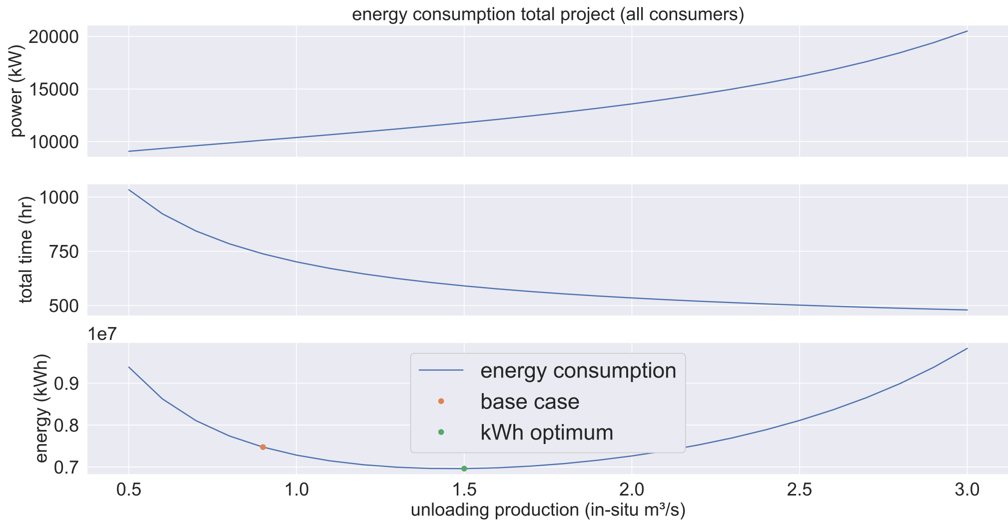

Figure 5.14: Consequences of *unloading production* (in-situ m^3/s) optimisation on in terms of power requirement (kW), duration (h), and energy consumption (kWh) for the *total project*; presenting the work point for the base case and the optimal work point in terms of kWh

The emission consumption during the increase of production is visible in Figure 5.15, subdivided per dredge event. Note that only the discharge production influences the emission consumption during the discharge. The corresponding project costs are shown in Figure 5.16. The results of the CO_2 optimisation are summarised in Table 5.5. Note that for the calculations of the costs only the operational vessel costs are taken into account, the extra costs for the necessary booster pump equipment is not included in this analysis. The extra costs of the fuel consumption of the booster pumps is included in the analysis.

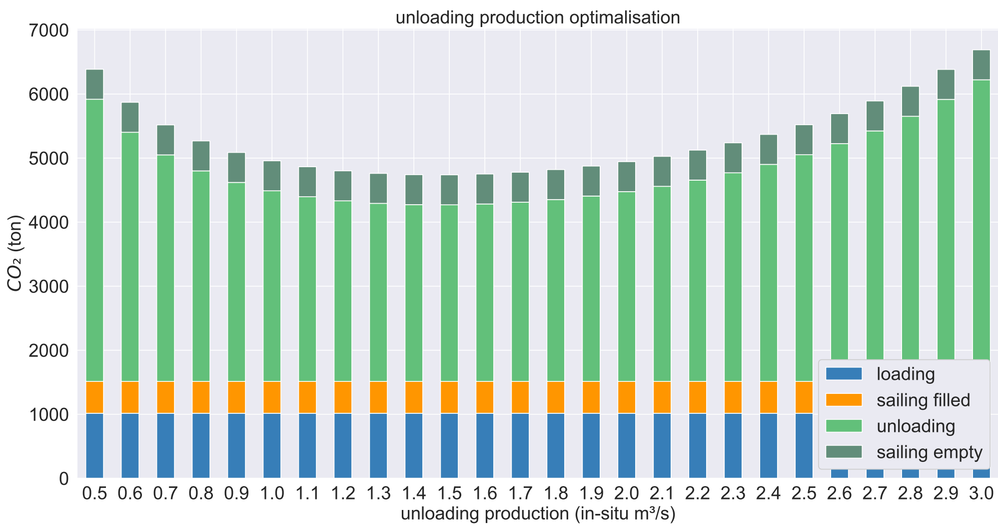

Figure 5.15: Consequences of *unloading production* (m^3/s) optimisation in terms of emitted CO_2 on a *project level*, presenting the emissions per cycle event; the optimal work method with an unloading production of 1.5 in-situ m^3/s is found

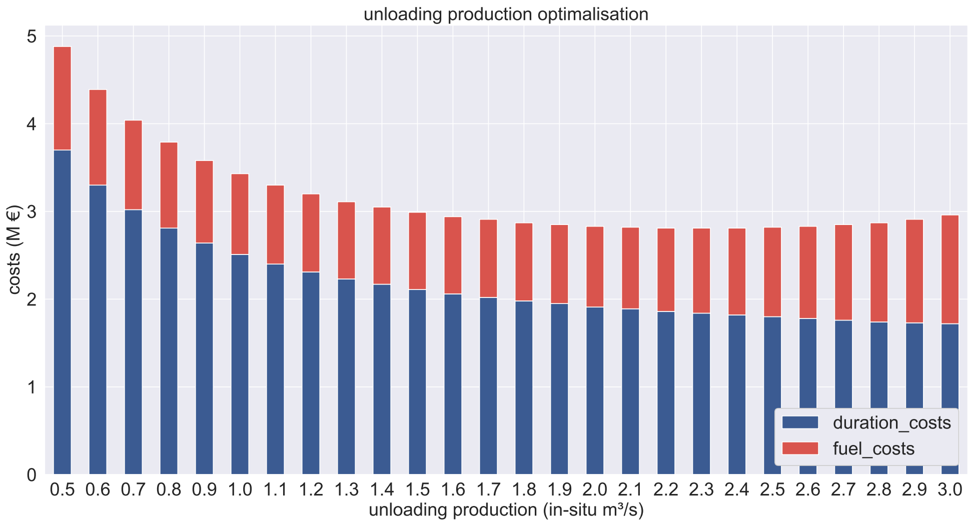

Figure 5.16: Consequences of *unloading production* (m^3/s) optimisation in terms of project costs on a *project level*, presenting the costs divided in costs for the equipment being on site and in fuel and lubricants costs

Table 5.5: Comparison of the *base case* work method with the CO_2 *optimisation* work method for *unloading production* optimisation; model output presented in terms of emitted CO_2 (tons), project duration (days), and project costs (M €)

Work method	**Unloading prod**	CO_2 **(tons)**	**Duration (days)**	**Costs (M euros)**
Base case	0.9	5088	30.75	3.58
Minimal CO_2	1.5	4738	24.6	2.99
	Difference	350 (- 7.4 %)	6.05 (-20 %)	1.57 (-16.48 %)

5.2.4. Vessel type

In the previous subsections, operational measures were discussed. These measures can be taken when the vessel is already selected. When the type of vessel is still to be determined, a new solution space opens up. In this subsection, the project is simulated as if executed with different vessel types.

The size of the vessel together with the vessel's accessibility are often the determining factor. The bigger the vessel, the more material can be loaded per cycle, en often the shorter the project duration. The size of the vessel has also limitations in the navigability of shallow waters, since the higher the payload of the vessel, the bigger the vessels draught. The larger the vessel, the larger the distance until the shore and thus the longer the discharge pipeline. But the larger the vessel, often the larger the main power consumers on board of a vessel, and the larger the fuel consumption. The fuel consumption could still be lower per m^3 in an absolute sense. The vessel speed of large hoppers is also larger than the maximal vessel speed of small hopper, which decreases the project duration. Since so much parameters are involved, a simulation is run with a *small*, *medium*,*large*, and a *jumbo* hopper where all these parameters are integrated in the simulation. A schematic overview of the situation is visible in Figure 5.17. For the cross-shore profile of the location, the empirical equation for the equilibrium beach profile proposed by Bruun (1954) could be applied (Bosboom & Stive, 2015). The equation consists of a simple power law relating water depth h to the offshore distance x' (where x' = 0 is around the mean waterline and is positive in the offshore direction), according to:

$$h = A(x')^m \tag{5.1}$$

Where:

h	=	water depth	(m)
A	=	shape factor	(0.086),
x' =	=	distance offshore	(m)
m	=	shape factor exponent	(0.64)

Since no shape factors are available for the exact location of Texel, the location Noordwijk is taken into account. The corresponding accessibility, and length of the discharge pipe for each hopper size, which is found in Table 5.6. The rest of the vessel characteristics that are used in the simulation can be found in the corresponding notebook, see Appendix D for a link to the corresponding notebook.

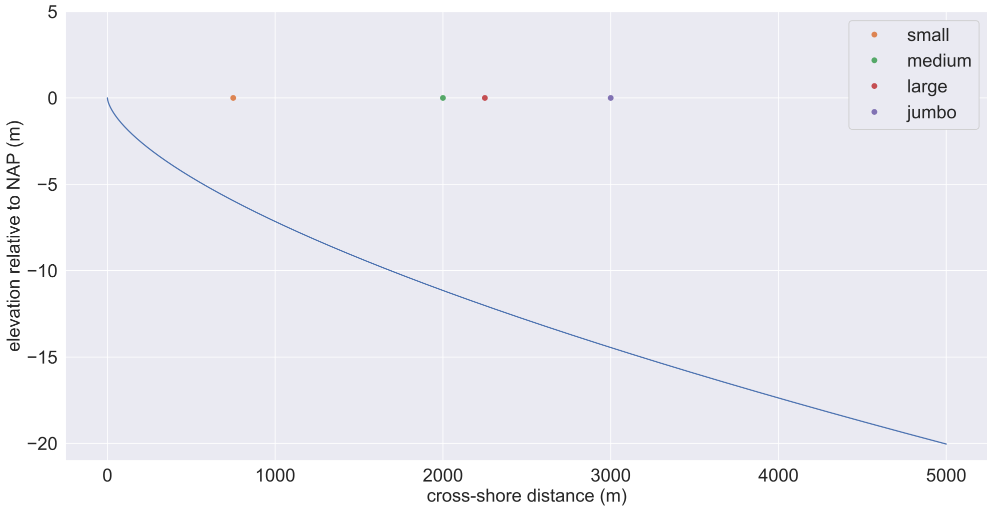

Figure 5.17: Schematic overview accessibility of a various TSHD sizes performing a sand nourishment with *pumping* as unloading method

Table 5.6: Hopper characteristics draught (m) and discharge pipeline length (m) for different vessel types

	Small	**Medium**	**Large**	**Jumbo**
Draught loaded	6 m	9 m	10 m	14
Length discharge pipeline	75 m	2000 m	2250 m	3000 m
Sailing distance	14.75 km	13.28 km	13.00 km	12.5 km

The results of the simulation concerning the project duration are shown in Figure 5.18. It is visible that the jumbo hopper is the most efficient one in terms of duration. This is due to the large capacity, and thus the fewer trips that the hopper needs to make in order to finish the project. The time that the small hopper needs in order to finish the project is more than three times larger than the project duration of the jumbo hopper. In Figure 5.19 the CO_2 emissions are plotted for the various vessel types. The jumbo hopper is the largest energy consumer and emits the largest amount of CO_2. In Table 5.7 the project output is summarised.

Table 5.7: Comparison of the *vessel types*; model output presented in terms of emitted CO_2 (tons), and project duration (days)

Vessel size	CO_2 **(tons)**	**Duration (days)**
Small	3168	55
Medium	4801	30
Large	4345	25
Jumbo	6011	18

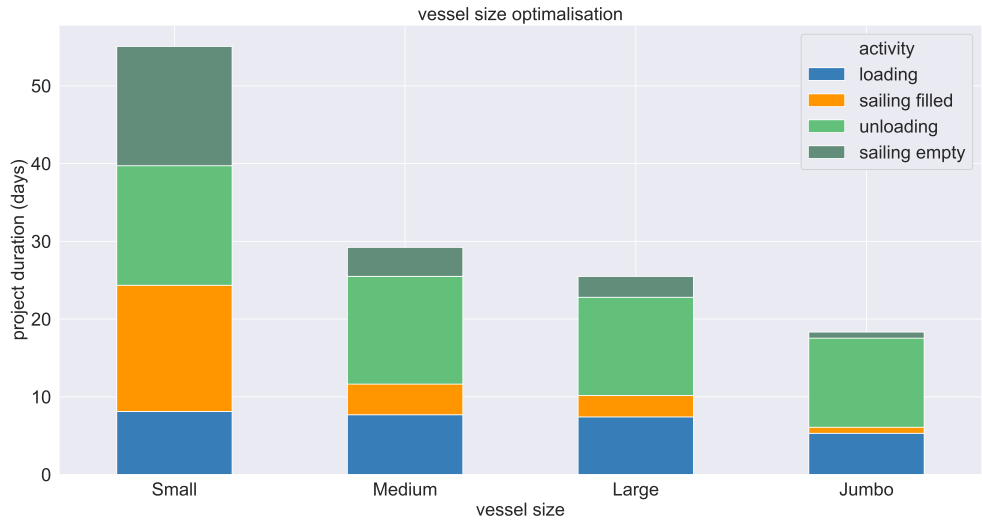

Figure 5.18: Consequences of *vessel type* optimisation in terms of project duration (days) on a *project level*, presenting the duration per cycle event; the optimal vessel type is the *Jumbo* TSHD

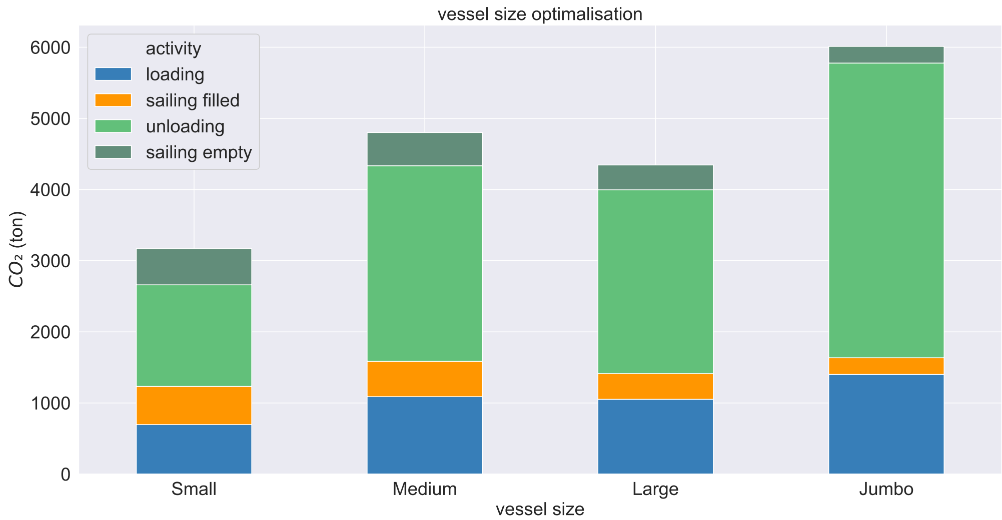

Figure 5.19: Consequences of *vessel type* optimisation in terms of emitted CO_2 on a *project level*, presenting the emissions per cycle event; the optimal vessel type is the *small* TSHD

5.2.5. Alternative Fuel type

A choice to use alternative fuels can lead to a reduction in CO_2 emissions. The fuels that originate from fossil fuels (MDO, HFO, MGO) are currently widely used in the maritime sector.

Fuels can contribute to more environmentally friendly solutions in various ways, and betting on one of these technologies could be an option. One hand, this can be achieved through the use of sustainable fuels that have been made from the synthesis of biomass into fuels (bio-fuels). On the other hand, this can also be achieved by using fuels that are developed via electrolysis based on renewable sources such as wind and sun (Hydrogen, CNG, LPG or LNG). These different fuels have different energy efficiencies, but also differ in storage technology and motor technology.

Figure 5.20 provides an indication of the impact of the usage of different fuel types. The fuels shown here are fuels that are used in heave transport (Chryssakis, 2013). The energy efficiency of the fuel is included in the calculation, together with the carbon content that the fuels contain. The amount of energy that is calculated corresponds directly to the amount of fuel that would be required for this. In Appendix A these factors can also be found per fuel. The impact of the differences in engine techniques that accompany the implementation of alternative fuels is not yet included in the model. The specific fuel consumption of the vessels can differ per fuel type due to motor technology. This should be further investigated. Even without taking this into account, it already gives an indication to what extent the level of CO_2 can be reduced with the use of alternative fuels and it also proves the functionality and limitations of the model in this area at current development.

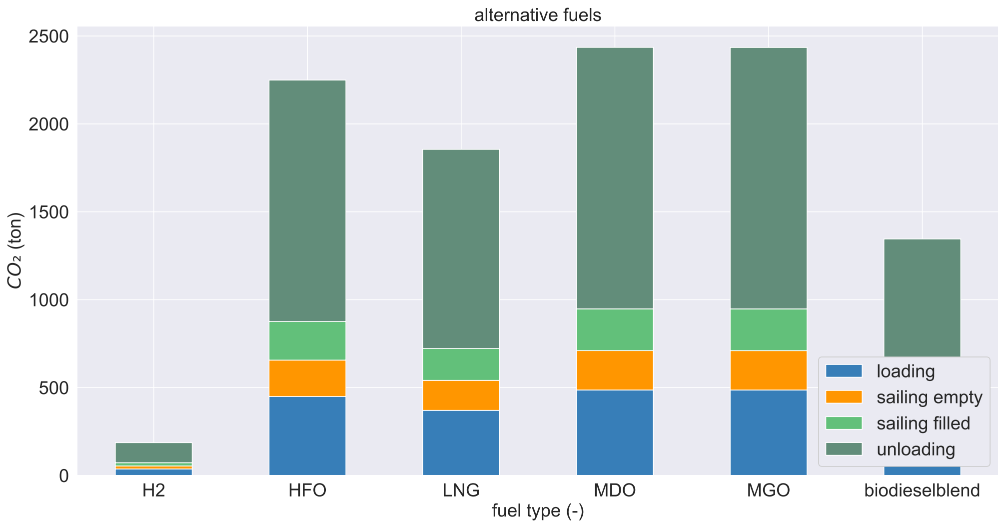

Figure 5.20: Consequences of *fuel type* optimisation in terms of emitted CO_2 on a *project level*, presenting the emissions per cycle event

Even though it is an obvious conclusion, CO_2 can also be reduced by implementing a different fuel. This study uses a specific engine with specific engine efficiencies and data on the fuel consumption of existing equipment. It must be further investigated what the impact of these factors is on the use of an alternative fuel.

5.3. Future policy measures

Besides the operational aspects that can be influenced by a the contractor, there are other aspects that determine the amount of emitted CO_2, as explained in Chapter 2. In this section, the implication of adapting policy measures concerning the project boundaries and the internalisation of climate change costs are discussed.

5.3.1. Adapting project boundaries

Often the dredging location and placement location are already determined by the boundaries of the tender. These boundary conditions determine the extraction depth, sailing distance, and sometimes also the dump method. Two simulations show the opportunities for CO_2 reduction when clients and policy makers would be more flexible towards these project boundaries. The simulations are discussed in the following sub-sections.

Relocate the dredging location

The volume that is dredged every year to maintain our coastal foundation is determined by law. The coastal foundation is the zone between the dunes and sea dikes and the ongoing Normal Amsterdam Level 20 m depth line in the sea. The extraction sites (dredging locations) of a standard dredging project are therefore outside this 20 m depth line. This boundary naturally includes a certain sailing distance and the depth of at least 20 m at which dredging takes place. Although it is outside the control of the contractor to deviate from these regulations, the impact of this is being investigated. This paragraph quantifies the impact of adapting the dredging location.

The dredging location of the base case project corresponds with an extraction depth of 24 *m*. The dredging location of the base case corresponds to an offshore distance of 15 *km*, while the 20 *m* depth corresponds to an offshore distance of 5 *km*. It is assumed that dredging is not allowed within the depth of 20 m, as this would impact the coastal foundation. Yet it is investigated what the impact would be of relocating the dredging location in the onshore direction, up to the 20 *m* depth line. The same cross-shore profile as mentioned before in this chapter is assumed. The formula of Bruun does not hold outside the 20 *m* depth area (Bosboom & Stive, 2015). Further development of the cross-shore profile is assumed to decrease linearly between the 20 *m* and 24 *m* depth. The connection point for the base case is located 2000 *m* in offshore direction, and remains constant during the simulation.

Relocating the dredging site in onshore direction, decreases the sailing distance and the dredging depth. The impact of this test case is shown in Figure 5.21 and Figure 5.22 where the project duration and CO_2 emissions have been plotted per dredging location in offshore direction *km* . The reduced distance per simulation naturally has a direct effect because the time of the sailing events is reduced and therefore the CO_2 emissions. The decrease in depth also has an effect on the CO_2 emission, since a lower vacuum is always required on the suction side of the pump. Table 5.8 indicates how much contribution the two components make to the impact of the CO_2 reduction.

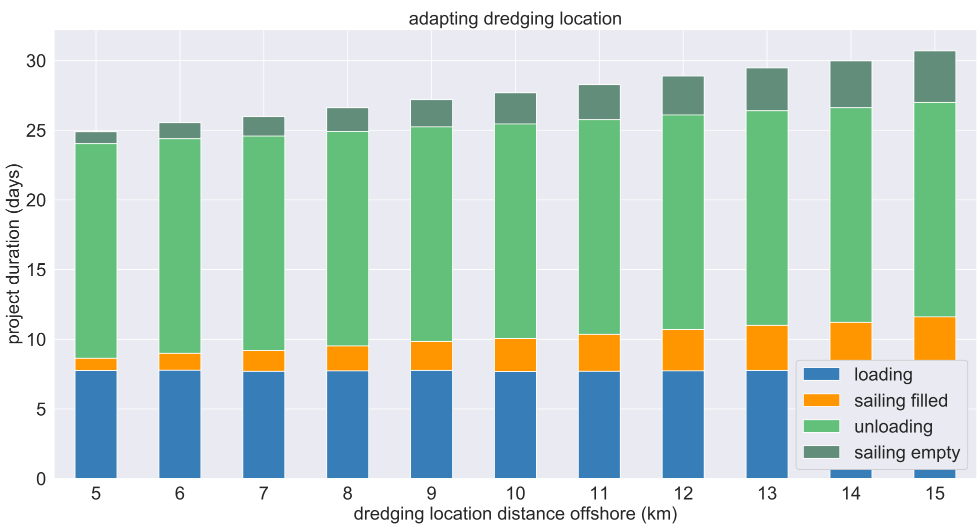

Figure 5.21: Consequences of *adapting the dredging location* optimisation in terms of project duration (days) on a *project level*, presenting the duration per cycle event

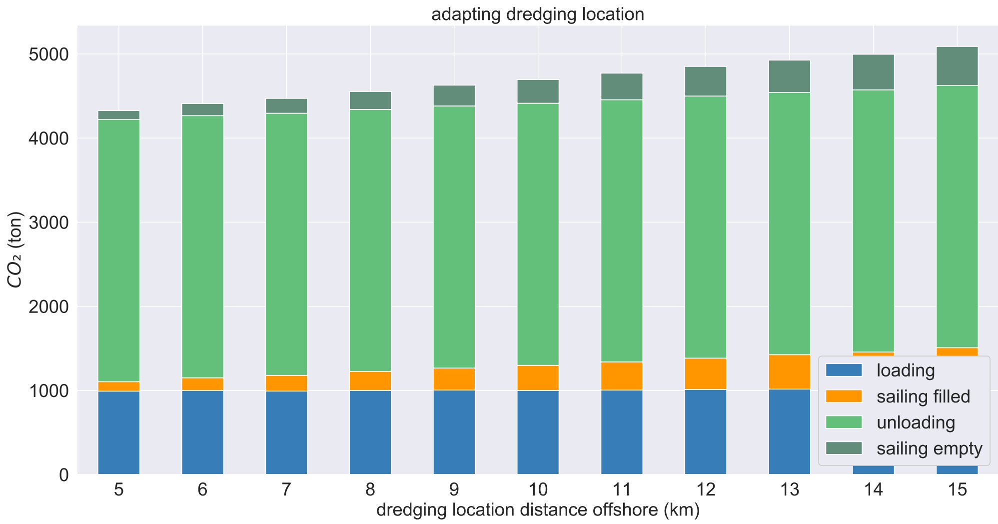

Figure 5.22: Consequences of *adapting the dredging location* in terms of emitted CO_2 on a *project level*, presenting the emissions per cycle event

Table 5.8: Comparison of the *base case* work method with the CO_2 *optimisation* work method for *dredging within the -20 m depth contour* optimisation; model output presented in terms of emitted CO_2 (tons), project duration (days), and project costs (M €)

Work method	**depth (m)**	**distance (km)**	CO_2 **(tons)**	**Duration (days)**	**Costs (M euros)**
Base case	24	13.28	5096	30.75	3.57
Minimal CO_2	20	3	4326	24.9	2.93
Difference			770 (-15.12 %)	5.85 (- 19.02 %)	0.64 (-17.93%)

Type of nourishment

The volume that is needed for the coastline preservation yearly, is divided in a part for beach nourishment and a part for foreshore nourishment. The type of nourishment partly determines the type of unloading method. Unloading by dumping is only possible for foreshore nourishment, and requires less energy than the other methods (Gonçalves Castro et al., 2014). For beach nourishment, pumping or rainbowing could be applied, where the contractor tries to unload the vessel as quickly as possible. The emissions differs per unloading method: for the relatively quick process of dumping, the least emissions are released. For rainbowing and pumping, more emissions are released.

The base case project is simulated with the unloading method: *pumping*, with a discharge pipe with a length of 2 *km*. The impact of this unloading method is compared with other unloading methods. To be able to compare the different unloading methods, the dredging and the dump locations are the same in all simulations. In reality, the different unloading methods offer options to different dumping locations. Rainbowing can be performed much closer to the coastline, and dumping is performed in the foreshore, further away in offshore direction. For this specific case it was not possible to perform dumping (because it had to be a beach nourishment given the tender boundaries) or to rainbow (because the vessel cannot position closer to the coastline due to it's accessibility). To give an indication of the different dump methods and the associated CO_2 emissions, the simulation is done with different dump methods. In addition to dumping and rainbowing, the impact of pumping is simulated with a 1 km discharge line instead of a 2 km discharge line. In Figure 5.23 the three simulations are plotted next to each other, which shows that the dumping method yields significantly less CO_2. The results are also summarised in Table 5.9.

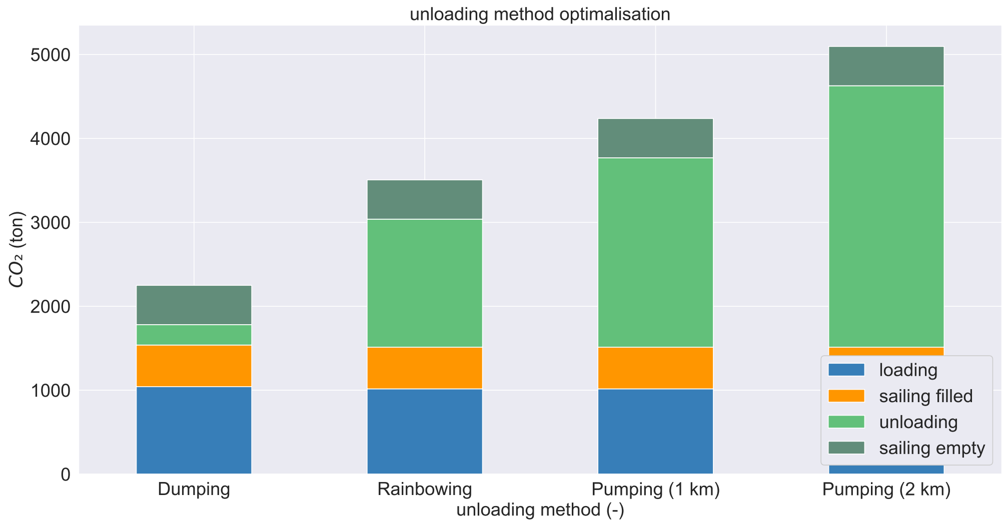

Figure 5.23: Consequences of *unloading method* optimisation in terms of emitted CO_2 on a *project level*, presenting the emissions per cycle event

Table 5.9: Comparison of the work methods concerning *unloading method* optimisation; model output presented in terms of emitted CO_2 (tons), project duration (days), and project costs (M €)

Work method	CO_2 **(tons)**	**Duration (days)**	**Costs (M euros)**
Pumping 2 km (base case)	5096	30.75	3.58
Dumping	2249	17.28	1.89
Rainbowing	3506	30.75	3.29
Pumping 1km	4237	30.75	3.42

If the distribution in the volume of sand in that is added to the foreshore and added to the beach annually, this would offer opportunities to reduce CO_2. The simulation has shown that dumping does indeed emit far less CO_2 than the other methods. If the sand volume of this project was dumped at the same point as the connection point instead of being pumped to the beach, it would yield 55.9 % CO_2 reduction.

5.3.2. Internalisation of external costs

The aim of internalisation of external dredging costs is to maximise the contribution of dredging to society's welfare. Internalisation can be achieved with various policy measures, including market-based instruments (i.e. increasing fuel prices, CO_2 taxes and tradable permits), regulatory instruments (i.e. prohibit fuels) and voluntary instruments (such as initiatives and agreements with the dredging industry to reduce CO_2 emissions from new equipment).

To show the implication of these measures on decision-making of a dredging contractor, two simulations are done. The examples chosen for the internalisation of climate change effects of CO_2 emissions, are the increase in fuel prices and the implementation of a CO_2 taxation system. Since ultimately, the *total project costs* is the deciding factor for a contractor to base decision making on, these measures result in a more environmental friendly way of operating and thus CO_2 emissions could be reduced.
To demonstrate the decision support provided by the model, the simulation of reducing vessel speed has been used as a proof of concept. In the simulated examples in this chapter, the total project costs are subdivided in the fuel costs and weekly vessel rates. The chosen strategy for a work method of a contractor influences both the fuel costs and the total costs for the equipment being on site. In Figure 5.8 the total projects are plotted where the following numbers (as a proof of concept) are assumed: the fuel price of 0.65 euros per liter MDO and a weekly vessel rate of 600 000 euros. In terms of costs, the most optimal work method is the work method with an vessel speed of 8.5 m/s. Although the fuel costs are not the lowest for this work method,

the operational costs are lowest and dominate the fuel costs. Figure 5.24 shows a simulation with a fuel price that is three times higher than the previously discussed fuel price. A shift in the most optimal work method can be detected, and the strategy with a vessel speed of 6.5 m/s is preferred. Figure 5.25 shows a simulation where the impact of the implementation of a CO_2 taxation system is explored. The tax imposed is 200 euros per tonne emitted CO_2. A tax that is now being discussed by the Dutch government, to be implemented in 2030. This simulation, too, shows a shift in the most optimal work method concerning total project costs. The most favourable work method is now the work method with a vessel speed of 7.5 m/s. The increase of fuel price and the implementation of the taxation system are also simulated for the other measures (trail speed reduction, adapted unloading production, change in vessel size) and can be found in Appendix C.

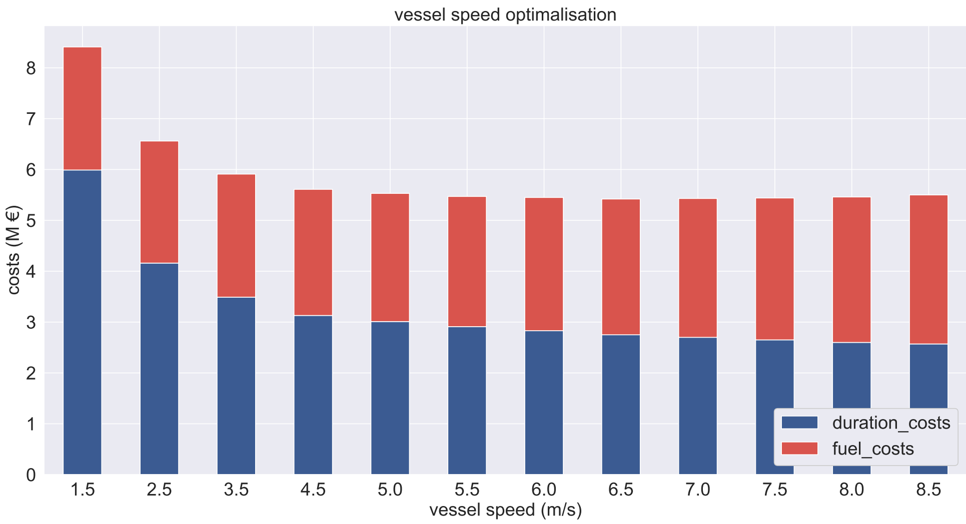

Figure 5.24: Consequences of *vessel speed* (m/s) optimisation in terms of project costs on a *project level*, presenting the costs divided in costs for the equipment being on site and in fuel and lubricants costs; taking an increase of fuel price into account of 300%

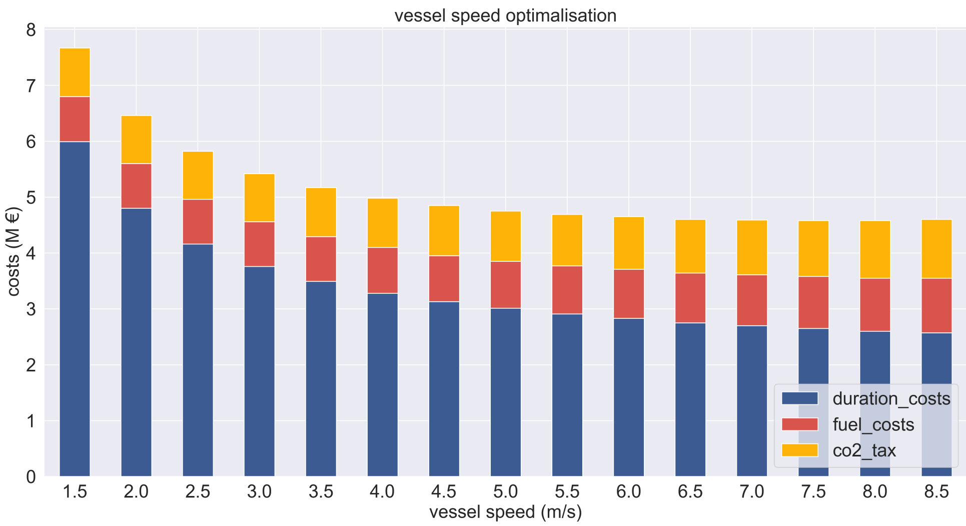

Figure 5.25: Consequences of *vessel speed* (m/s) optimisation in terms of project costs on a *project level*, presenting the costs divided in costs for the equipment being on site, fuel and lubricants costs, and CO_2 emission costs; taking a CO_2 tax of 200 € per ton into account

The tool could also be used when entering into a discussion with policy makers, such as Rijkswaterstaat

about the costs of achieving CO_2 reduction for Dutch coastline preservation. If for example in a tender it is explicitly asked for a 15% reduction, the price of this reduction can be calculated. With the model, a project can be simulated as it would conventionally be executed by a contractor. From the simulation it can be established how much it will cost extra to achieve the reduction, namely 0.4 Million euros on this project. Furthermore, the model demonstrates that the 15 % reduction is achieved when a tax of 1660 euros per tonne CO_2 is imposed or when an increase of fuel price by a factor of 10 is imposed.
It can be concluded that the tool supports the user in exploring policy impacts of fuel price increase or the implementation of a CO_2 taxation system.

5.4. Conclusion

As a proof-of-concept, the model was tested by applying it to a real case project. This resulted in the following two conclusions: the functionality of the model has proven to be useful, and it can be concluded that within the boundaries of a specific project a contractor is able to take measures that reduce the emitted CO_2. These two conclusions are further elaborated below.

First, the listed cases demonstrate that it supports the user in optimising the operational aspects of strategies to reduce the CO_2 emission. Using the model has shown that there are a number of operational aspects that a contractor can take to reduce the emitted CO_2 within the scope of a project the model has shown and that it can help the user to make decisions based on how a tender was requested. The model can quantify various performance indicators at both high-level (the overall project) and at a low-level (the cycle and specific vessel operations). The high-level approach allows the user to look for what is important in a certain tender: emitted CO_2, project duration, or project costs. Furthermore, low-level insight per dredging event per cycle allows the user to optimise certain vessel properties. It can be concluded that the functional requirements described in Chapter 3 are met. In addition to the functional requirements in chapter 3, a number of project adjustments are demonstrated that could reduce CO2 even further, but these are outside the decisive power of a contractor these so-called project aspects.

Second, the results of the optimisation cases are summarised to formulate quantifiable measures available to contractors to optimise dredging projects on CO_2 emission. The operational factors that influence the emitted CO_2 on project level result in the following conclusions:

i. By reducing the vessel speed or by using a different type of vessel , a project can be completed with fewer emissions, -14.9% and -37.9% correspondingly.

ii. It has been demonstrated, within the framework of this study, that a dredging company cannot further optimise on trail speed, assuming that a dredger always trails as fast as possible.

iii. Furthermore, an optimal discharge production can be found which reduces the CO_2 with -7.4%, it should be further investigated whether this is technically feasible, in order to actually be able to conclude whether this is indeed an option for a contractor.

Some project aspects that can reduce the emitted CO_2 are also considered.

iv. It has also been shown that adapting policy measures provides CO_2 reduction. When project boundaries are reconsidered and the contractor is allowed to operate within the -20 m depth contour, CO_2 can be reduced with -15.12%.

v. If the contractor is able to adapt the unloading method and perform a foreshore nourishment instead of a beach nourishment, 55.9% reduction is achieved. Furthermore, the model has proven its functionality in supporting decision-making when internalisation of externals costs are further implemented.

All in all, it can be concluded that the extent of reduction depends on the project boundaries. As discussed earlier, a reduction target of 30% in 2030 has been set by RWS. It can be concluded that this reduction cannot be achieved if the vessel has already been selected and the project boundaries are already determined. A combination of the operational aspects provides a maximal reduction of 5.10 within the boundaries of this project. This is the maximal theoretical reduction that could be achieved, it must be further investigated whether this is technical feasible. Further reduction can be achieved by choosing another vessel, by using a different fuel type, or when policy measures are adjusted. The financial implications of the measures are also listed in the Tables, expressed in cost-effectiveness of the measure. The cost-effectiveness is expressed in euros per amount of reduced CO_2 emission regarding the base case project.

Table 5.10: Results of optimisation measures found making use of the model; optimisation in terms of $\Delta\ CO_2$ (ton) and (%) presented relatively to the output of the base case project

Measures	**$\Delta\ CO_2$ (ton)**	**$\Delta\ CO_2$ (%)**
Operational measures		
Vessel speed reduction	759	14.9
Unloading production optimisation	350	7.4
Vessel type optimisation	2159	37.9
Policy measures		
Adapting dredging location	770	15.12
Adapted type of nourishment (and unloading method)	2847	55.9
Implementation of CO_2 system (200 euro / ton CO_2)	51	1

6 Discussion and conclusion

This Chapter explains the results of the analyses of the conducted research. First it discusses the interpretation of the most significant finding by acknowledging the study's limitations in Section 6.1. Afterwards, Section 6.2 formulates the conclusion of the thesis. To conclude this Chapter, in Section 6.3, suggestions are made for further research.

6.1. Discussion

In this section the interpretation of the results are further explained, together with the study's limitations. The discussion is divided into two topics: the explanation of the model set-up and the model assumptions.

6.1.1. Model set-up

Part of this thesis was committed to answer Sub-question (iii.): *How to develop and validate a model to assess the CO_2 emissions performance and corresponding financial implication of a project strategy?* A reflection on the extent to which the model set-up has succeeded towards this goal follows.

The functional requirements of the model are formulated to make the assessment of work methods possible. These are discussed one by one. The first requirement states: "support the user in finding emission reduction measures". Simulations of different working methods are performed, which resulted in finding different working methods with reduced CO_2 emission. It shows that this requirement is met. However, only selecting a TSHD for testing other working methods is an option. Although this type of equipment is the most used vessel for sand nourishment projects of the Dutch coast, other types of dredging projects could require other equipment types. The model set up does not include the specific characteristics of other vessels such as BHD, CSD, or barges. The second functional requirement is "support the user in decision making on project level". It resulted in including various KPIs (project duration, energy consumption, fuel consumption, emitted CO_2, and project costs) in the model. The last requirement is: "provide down-drilled insight". The model demonstrates how to make an analysis based on the four defined phases in the production cycle, and the model analyses the power consumption per main consumer. Future development should allow down-drilling into the sub-stages of these events and add downtime events. Stages such as acceleration and deceleration stages of the vessel, manoeuvring, refuelling, waiting for weather conditions, downtime, and (de)mobilisation of the vessel could improve the depth of the analyses.

6.1.2. Model assumptions

The model generates output concerning energy consumption, fuel consumption, and CO_2 emission. The model also generates output concerning project duration and project costs. This part reflects on the extent to which the model output is realistic, and also on *why* and *how* the output would differ from real-time processes.

The model calculates all relations regarding energy consumption for the two primary consumers explicitly:

the propellers and the inboard dredge pumps. The rest of the energy consumers (bow thrusters, board net, and jet pumps), are implemented as standardised input. A loading factor per energy consumer is added per dredge stage. This loading factor is determined by Van Oord based on data analysis with fuel logs per consumer. Although this increases the prediction per standardised consumer on the total energy consumption, this is a simplified representation of real-time proceedings. The effect that the energy consumers have on each other when work methods change is therefore not considered.

Calm weather conditions are assumed when simulating a dredging project resulting in the assumption of continuous operation. There are no limitations regarding weather conditions that trigger the vessel to stop operating during the simulation. When weather limitations for a vessel are added, this would better reflect real-time processes. To increase the model's functionality, the model uses the expected weather conditions during an operation period of the project. In this simulation, the model is able to make a more accurate estimation of the project duration and costs. A vessel is stationary during this downtime, it is assumed that it hardly influences the amount of emissions emitted during a project. The same effect on project duration and costs applies to the downtime due to technical failures of the equipment. A workweek of 168 operational hours per week has been assumed, without any form of downtime. The model could simulate unrealistic project duration. Within the dredging industry, it is customary to adopt an operational workweek of 150 hours per week to include the downtime.

The model simulates the sailing stages based on the assumption that the maximal vessel speed is the absolute vessel speed achieved. This absolute vessel speed is translated into duration of stages and effects on the total energy consumption. The use of the absolute vessel speed makes it accessible to simulate a project without any further project details quickly. The disadvantage of making use of the absolute vessel speed is twofold. First, acceleration and deceleration stages are left out of scope since relatively few acceleration and deceleration takes place during the sailing events. The effect of omitting these phases is more significant with small sailing distances than at larger sailing distances. Secondly, by making use of the absolute vessel speed, the simulation does not include the effects of (tidal) current velocities and the squat effect on vessels operating in shallow water. In the case of squat effects, this results in an overestimation of the actual vessel speed achieved. In the case of the tidal current, the effects of the tide are balance each other out over the entire project. However, leaving this out of scope limits the possibility to investigate how a contractor could benefit from tidal effects in terms of energy consumption.

The settling process is simulated based on a loading curve that must be supplied by the production estimators. A certain soil type, vessel dimension's, and production that the vessel achieves with corresponding operational conditions determine the loading curve of a vessel. The advantage of using a loading curve is that it provides a fast way to run ship specific simulations. The disadvantage is that a loading curve must be available that matches the specific operational conditions. Under or over-estimation of the loading duration are generated with a mismatching loading curve. The simulation of the case study assumes a loading curve without any overflow losses. This assumption is made because of the operational conditions of the case study, a project on the Dutch coast where coarse sand is situated.

During the validation phase of the model, the generated output concerning emitted CO_2 is compared with the results of the indicative emission method of the CEDA. This method presents a benchmark of expected emissions related to vessel size and dump method. The model generates output that corresponds to these benchmarks only partly. As already noted in the validation chapter, the deviation of the benchmark could not be fully explained with the available data. The CEDA output is based on actual vessels of the EUDA fleet of which the detailed data was not available. With the available data the model could be validated more accurate.

Another step to validate the output could be added, where analysing historical fuel logs provide insight on the actual energy consumption. The reason to analyse fuel logs increases the validation of the model in two ways. First the deviation of the energy consumption and corresponding fuel consumption could be analysed to indicate the consistency during an event. It could be evaluated if the calculated required power per event could indeed be used as an average. Second, fuel logs could be analysed to compare the calculated fuel consumption based on the operational setttings with the actual fuel consumption.

In the calculations of the unloading stage for rainbowing and pumping, some assumptions have been made to calculate the energy losses during the process of hydraulic transportation. An increase in linear mixture density is assumed in the suction pipeline from the beginning of the suction pipeline until the location of the dredge pump during unloading. Bernoulli's equation and the continuity equation, implicitly consider a not changing mixture velocity in a pipeline. For this reason, the equations strictly do not hold. Since all simulations assume the use of the Bernoulli equation, the output of the model can be compared relatively.

There are a lot of uncertainties with dredging projects. Adding the option for a Monte Carlo simulation and specifically adding these uncertainties would result in better results. Instead of a fixed value, a range would be the outcome of the model.

6.2. Conclusion

The necessity to gain more insight into CO_2 emissions on a project level is triggered by an increase in focus on environmental awareness, which has also caused a shift in the client demand in the dredging industry. A first experimental tender is set out by RWS, where explicitly CO_2 reduction is requested. It has led to the ambition of finding out how a contractor like Van Oord could best operate to ascertain minimal CO_2 emission. This ambition resulted in the following research objective:

"To quantify the consequences at project level of CO_2 emission reduction strategies available to contractors, while providing insight in the corresponding financial implications of such strategies"

To achieve this research objective, first a literature study was conducted to indicate the possible strategies that could reduce the emitted CO_2. The indicated factors are distinguished between the *project aspects* (determined by the boundaries of the tender) and the *operational aspects* (determined by the work method strategy of the contractor) and the *policy measures* (indirectly influence the strategy of a contractor).

Another outcome of the literature study, is the indication of two methods that have been suggested to indicate the amount of CO_2 emissions during dredging operations. The first method is an indicative method presented by the CEDA, and the second one is based on average energy consumption presented by the IMO. Although both methods can quickly lead to indications of emissions based on standardised input, the methods do not include all parameters that are important concerning the total CO_2 emission on a project level as noted in the literature study. Part of the solution space in the tender phase of the project for engineers decreases and possible optimisations cannot be found.

To quantify the consequences of strategies, the model objective is to generate: emitted CO_2, project duration, and project costs. By modelling these different aspects, the user can make a data-driven decision on the strategy of a dredging project. The functional requirements of the model are to support the user in finding emission reduction strategies, to support the user in decision making on a project level, and to provide down-drilled insight in KPIs on project level and per dredging stage. The model concept that is chosen is the OpenCLSim available at the GitHub of the TU Delft Hydraulic Engineering department, which is based on Discrete Event Simulation (DES) and Agent Based Simulation (ABS). It is developed in a dedicated Simpy environment in Python. The reason for this concept is threefold. First, this package has already been tested and proved to be useful for the simulation of dredging projects within Van Oord. Secondly, it reduces the computational time when many work methods must be simulated. Finally, the functional requirements and the characteristics of the dredging cycle meet the characteristics of DES and ABS, since the project flow of a dredging project can be seen a series of discrete events, and the equipment in the model can be seen as autonomous entities (agents) and can display proactive behaviour. The structure of the model can be subdivided into *equipment*, *activities*, *sites*, and *costs*. Per stage of the dredging cycle the level of emissions is calculated, based on the calculated power requirement, which depends on operational parameters and hopper characteristics. The power requirement is calculated per main energy consumer. The power requirement of the *propellers* and the *inboard dredge pump* is explicitly calculated based on the indicated operational parameters and hopper characteristics. The power requirement of the other consumers (jet pumps, bow thrusters, board net) is calculated based on standardised input (Van Oord data) and the duration that the equipment is on site.

The approach that is used to validate the model consists of three different steps. First, the model's internal components are successfully validated by using Test Driven Development. Second, the output of the model is cross-referenced with the indicative numbers about CO_2 emission presented by the CEDA. The level of emitted CO_2 falls (partly) within these benchmarks. As a final validation step, a case study is simulated, and the results are compared with historical project data about the duration per event and the fuel consumption. For this stage of the development, the model's output is assumed acceptable, since most of the results fall within a range of <5%. The fuel consumption and the project duration exceed this number, which can be investigated in further research.

To investigate which strategy a contractor must choose to minimise CO_2 emissions at project level, the model is tested by applying it to a real case project. This case study acts as a proof-of-concept, and presents the potential of the use in the tender phase of a project. This resulted in the following two conclusions: the functionality of the model has proven to be useful, and it can be concluded that within the boundaries of a specific project a contractor is able to take strategies that reduce the emitted CO_2. These two conclusions are further elaborated below.

First, the listed cases demonstrate that it supports the user in optimising the operational aspects of strategies to reduce the CO_2 emission. The model has shown that there are a number of operational aspects that a contractor can optimise to reduce the emitted CO_2 within the scope of a project, and that it can help the user to make decisions based on how a tender was requested. The model can quantify various performance indicators at both high-level (the overall project) and at a low-level (the cycle and specific vessel operations). The high-level approach allows the user to look for what is important in a certain tender: emitted CO_2, project duration, or project costs. Furthermore, low-level insight per dredging event per cycle allows the user to optimise certain vessel properties. It can be concluded that the functional requirements described in Chapter 3 are met. In addition to the functional requirements in chapter 3, a number of project adjustments are demonstrated that could reduce CO_2 even further, but these are outside the decisive power of a contractor these so-called project aspects.

Second, the results of the optimisation cases are summarised to formulate quantifiable strategies available to contractors to optimise dredging projects based on minimising CO_2 emission. The conclusions are specific for the tested case and thus the tested equipment with corresponding vessel characteristics. The operational factors that influence the emitted CO_2 on project level result in the following conclusions.:

i. By reducing the vessel speed or by using a different type of vessel , a project can be completed with fewer emissions, -14.9% and -37.9% correspondingly.

ii. It has been demonstrated, within the framework of this study, that a dredging company cannot further optimise on trail speed, assuming that a dredger always trails as fast as possible.

iii. Furthermore, an optimal discharge production can be found which reduces the CO_2 emissions with -7.4%, it should be further investigated whether this is technically feasible, in order to actually be able to conclude whether this is indeed an option for a contractor.

Adapting policy measures could also lead to the reduction of emitted CO_2 on project level. Although this is outside the decisive power of a contractor, there are possibilities that are further elaborated on below.

iv. By relocating the dredging location in onshore direction towards the start of the coastal foundation (at the -20 m depth contour) it has been shown that CO_2 can be reduced with -15.12%.

v. If the contractor is able to adapt the unloading method and perform a foreshore nourishment instead of a beach nourishment, 55.9% reduction is achieved.

vi. Furthermore, the model has proven its functionality in supporting decision-making when internalisation of externals costs are further implemented by policy makers. If a strategy of reducing vessel speed is chosen, the implementation of a CO_2 taxation system of 200 € per ton ensures only a reduction of -1% in CO_2 emissions.

All in all, it can be concluded that the extent of reduction depends on the project boundaries. As discussed earlier, a reduction target of 30% in 2030 has been set by RWS. It can be concluded that this reduction cannot be achieved if the vessel has already been selected and the project boundaries are already determined. A combination of the operational aspects provides a maximal reduction of -22.3% within the boundaries of this project. This is the maximal theoretical reduction that could be achieved, it must be further investigated whether this is technical feasible. Further reduction can be achieved by choosing another vessel, by using a different fuel type, or when policy measures are adjusted. In Table 6.1 these results are summarised.

Table 6.1: Results of optimisation measures found making use of the model; optimisation in terms of Δ CO_2 (ton) and (%) presented relatively to the output of the base case project

Measures	**Δ CO_2 (ton)**	**Δ CO_2 (%)**
Operational measures		
Vessel speed reduction	759	14.9
Unloading production optimisation	350	7.4
Vessel type optimisation	2159	37.9
Policy measures		
Adapting dredging location	770	15.12
Adapted type of nourishment (and unloading method)	2847	55.9
Implementation of CO_2 system (200 euro / ton CO_2)	51	1

6.3. Recommendations

The assessment of dredging projects can be done by using the model developed in this thesis research. Future research could include elements to improve the model and to increase its functionality. This section formulates these components in a set of recommendations.

This research has indicated a method to calculate the energy consumption per dredging stage for a TSHD. The relations to calculate the required power and event duration are specified on hopper characteristics and do not apply for other vessel types directly. To be able to test even more project strategies, the model could be further developed such that alternative vessel types can be selected for the execution of a project. For example the relations regarding energy consumption of equipment such as Cutter Suction Dredgers, Backhoe Dredgers, and barges could be integrated. By integrating different types of equipment, the solution space increases for an engineer to be able to optimise on CO_2 emissions.

In the current state of the model the specified absolute vessel speed is used for the calculations of the energy consumption and the duration of the sailing events. Effects of (tidal) currents and squat effects due to shallow water are thus not taken into account, but do influence the energy performance of the vessel. Weather conditions and a depth profile could be added to take these effects into account. The power requirement can be calculated based on the actual vessel speed instead of the absolute vessel speed, and this will increase the accuracy of the calculated CO_2 emissions. In the next stage, the model could be used to simulate projects based on actual expected weather conditions. The outcome of these simulations could provide insight into optimisation possibilities such as: if it is, given weather forecasts, more energy efficient to start continuing operations immediately or to wait a little longer until the weather conditions are more favorable.

The duration of the loading stage of the hopper is now calculated based on a predefined loading curve, the maximal hopper load capacity, and a maximal considered overflow time. The loading curve is part of the model input. The integration of a calculation model about the settling process increases in the model's applicability. For example, the implementation of the Camp model in combination with grain size distributions of the dredge location will enable the user to estimate the loading time and overflow losses more accurate.

To further develop the user experience of the model for a contractor, manual entering of the hopper characteristic (e.g. vessel dimensions, operational costs, fuel consumption) could be replaced by the option to select a vessel. All specific parameters could then be applied automatically. The same principle holds for the characteristics of the dredging and placement sites. It would be a user friendly addition to the model, if the user is able to select the sites on a map and draw the preferred vessel route, instead of the now centre-to-centre used distance between two points.

A follow-up study to investigate operating in an emission-reduction manner should be conducted. In the conventional way of dredging, real-time, on-board production analysis drives the crew members to work most efficiently in terms of project duration. With the tangent method, crew members determine when the loading stage should end. With a changed performance indicator, a new way must be found to keep track of the performance. A study should be conducted on how to drive the crew members to operate most optimally in terms of CO_2 emission.

A
Carbon dioxide conversion factors

Carbon dioxide is not only produced during fuel combustion. Further upstream in the process the fuel must be transported to the refuelling station, and must be produced from the fuel extraction site. These activities also cause carbon dioxide emissions. In literature, three definitions are used concerning the definition of carbon dioxide emissions. The different expressions are explained below.

- Tank-to-wheels (TTW): This is the direct emission that are directly linked with the vessel operation and processes.
- Well-to-tank (WTW): This is all the indirect emission, from fuel provision from the well to the vessel tank. The losses during the production of the energy sources are also incorporated here.
- Well-to-wheels (WTW): The sum of the WTW and the TTW, thus the direcht and the indirect emissions. All losses from upstream the chain are included here.

In Table A.1, the conversion factors for various fuel types are presented. The TTW, WTW, and WTW conversion factors are presented to provide an insight in the ratio between these different conversion factors. For this research, the calculations will be made making use of the WTW conversion factor. As it is believed that this is the most honest way in assess the sustainability.

Table A.1: Conversion factors CEN-EN 16258

		Energy Factor		**GHG emission factor**			
	Density (d)	**TTW** (e_t)	**WTW** (e_w)	**TTW** (g_t)		**WTW** (g_w)	
Fuel type description	**kg/l**	**MJ/kg**	**MJ/kg**	**gCO_2e/MJ**	**kgCO_2e/kg**	**gCO_2e/MJ**	**kgCO_2e/kg**
Marine Gas Oil (MGO)	0,890	43,0	51,2	75,3	3,24	91,2	3,92
Liquefied Natural Gas (LNG)	-	48,5	-	56,2	2,7	69,5	3,37
Heavy Fuel Oil (HFO)	0,970	40,5	39,3	77,7	3,15	84,3	3,41
Marine Diesel Oil (MDO)	0,9	43,0	51,2	75,3	3,24	91,2	3,92
Bio-Diesel blend 95	0,835	42,8	52,7	71	3,04	88,8	3,8

B
Validation

B.1. Internal validation tests

Internal validation test: $w_{draghead}$

Table B.1 present the results for duration (h) of the modelled unit tests and analytical calculated functions, with varying draghead with. Doubling the value of the draghead width results in halving the duration phase, when no overflow losses are considered. The results show that this is indeed the case. A small error in duration is notable, since the model takes the intersection point between the jet production and the vacuum production, and calculates the duration based on this production.

Table B.1: Results internal validation test: draghead

Component	Unit	Condition (m/s)	Model value	Analytical value	Succeeded test
Duration loading	hr	0.5; 1.0; 2	1.036; 0.508; 0.253	1.0; 0.5; 0.25	yes
Power loading	kW	0.5; 1.0; 2	3734; 3982; 4496	3734; 3982; 4496	yes
Energy loading	kWh	0.5; 1.0; 2	3867; 2022; 1137	3734; 1991; 1124	yes
Fuel loading	l	0.5; 1.0; 2	3867; 2022; 1137	3734; 1991; 1124	yes
Costs loading	€	0.5; 1.0; 2	3867; 2022; 1137	3734; 1991; 1124	yes
CO_2 loading	kg	0.5; 1.0; 2	3867; 2022; 1137	3734; 1991; 1124	yes
number of cycles	-	0.5; 1.0; 2	1; 1; 1	1; 1; 1	yes
kg CO_2 / m^3	-	0.5; 1.0; 2	1.07; 0.56; 0.32	1.07; 0.56; 0.32	yes

Internal validation test: $h_{jetpenetration}$

Table B.2 present the results for duration (h) of the modelled unit tests and analytical calculated functions, with varying draghead with. Doubling the value of the jet penetration depth results in halving the duration phase, when no overflow losses are considered. The results show that this is indeed the case. A small error in duration is notable, since the model takes the intersection point between the jet production and the vacuum production, and calculates the duration based on this production.

Table B.2: Results internal validation test: draghead

Component	Unit	Condition (m/s)	Model value	Analytical value	Succeeded test
Duration loading	hr	0.5; 1.0; 2	1.036; 0.508; 0.253	1.0; 0.5; 0.25	yes
Power loading	kW	0.5; 1.0; 2	3734; 3982; 4496	3734; 3982; 4496	yes
Energy loading	kWh	0.5; 1.0; 2	3867; 2022; 1137	3734; 1991; 1124	yes
Fuel loading	l	0.5; 1.0; 2	3867; 2022; 1137	3734; 1991; 1124	yes
Costs loading	€	0.5; 1.0; 2	3867; 2022; 1137	3734; 1991; 1124	yes
CO_2 loading	kg	0.5; 1.0; 2	3867; 2022; 1137	3734; 1991; 1124	yes
number of cycles	-	0.5; 1.0; 2	1; 1; 1	1; 1; 1	yes
kg CO_2 / m^3	-	0.5; 1.0; 2	1.07; 0.56; 0.32	1.07; 0.56; 0.32	yes

Internal validation test: $Q_{g\,unloading}$

Table B.3 present the results for duration (h) of the modelled unit tests and analytical calculated functions, with varying the unloading rate. Doubling the value of the unloading rate results in halving the duration of that phase, when no overflow losses are considered. The results show that this is indeed the case. It is shown that the sailing empty activity is set at zero, since the hopper is not triggered to continue operating since all the material is already transported from the winning location to the dump location.

Table B.3: Results internal validation test: draghead

Component	Unit	Condition (m/s)	Model value	Analytical value	Succeeded test
Duration loading	hr	0.5; 1.0; 2	0.508; 0.508; 0.508	0.5; 0.5; 0.5	yes
Power loading	kW	0.5; 1.0; 2	3982; 3982; 3982	3982; 3982; 3982	yes
Energy loading	kWh	0.5; 1.0; 2	2022; 2022; 2022	1991; 1991; 1991	yes
Fuel loading	l	0.5; 1.0; 2	2022; 2022; 2022	1991; 1991; 1991	yes
Costs loading	€	0.5; 1.0; 2	2022; 2022; 2022	1991; 1991; 1991	yes
CO_2 loading	kg	0.5; 1.0; 2	0.56; 0.56; 0.56	0.55; 0.55; 0.55	yes
Duration sailing empty	hr	0.5; 1.0; 2	0; 0; 0	0; 0; 0	yes
Power sailing empty	kW	0.5; 1.0; 2	0; 0; 0	0; 0; 0	yes
Energy sailing empty	kWh	0.5; 1.0; 2	0; 0; 0	0; 0; 0	yes
Fuel sailing empty	l	0.5; 1.0; 2	0; 0; 0	0; 0; 0	yes
Costs sailing empty	€	0.5; 1.0; 2	0; 0; 0	0; 0; 0	yes
CO_2 sailing empty	kg	0.5; 1.0; 2	0; 0; 0	0; 0; 0	yes
Duration sailing filled	hr	0.5; 1.0; 2	1.0; 1.0; 1.0	1.0; 1.0; 1.0	yes
Power sailing filled	kW	0.5; 1.0; 2	1000; 1000; 1000	1000; 1000; 1000	yes
Energy sailing filled	kWh	0.5; 1.0; 2	1000; 1000; 1000	1000; 1000; 1000	yes
Fuel sailing filled	l	0.5; 1.0; 2	1000; 1000; 1000	1000; 1000; 1000	yes
Costs sailing filled	€	0.5; 1.0; 2	1000; 1000; 1000	1000; 1000; 1000	yes
CO_2 sailing filled	kg	0.5; 1.0; 2	0.28; 0.28; 0.28	0.28; 0.28; 0.28	yes
Duration unloading	hr	0.5; 1.0; 2	2.0; 1.0; 0.5	2.0; 1.0; 0.5	yes
Power unloading	kW	0.5; 1.0; 2	4718; 5376; 7146	4718; 5376; 7146	yes
Energy unloading	kWh	0.5; 1.0; 2	9436; 5376; 3573	9436; 5376; 3573	yes
Fuel unloading	l	0.5; 1.0; 2	9436; 5376; 3573	9436; 5376; 3573	yes
Costs unloading	€	0.5; 1.0; 2	9436; 5376; 3573	9436; 5376; 3573	yes
CO_2 unloading	kg	0.5; 1.0; 2	2.62; 1.49; 0.99	2.62; 1.49; 0.99	yes
number of cycles	-	0.5; 1.0; 2	1; 1; 1	1; 1; 1	yes
kg CO_2 / m^3	-	0.5; 1.0; 2	1.07; 0.56; 0.32	1.07; 0.56; 0.32	yes

Internal validation test: v_{vessel}

Table B.4 present the results for duration (h) of the modelled unit tests and analytical calculated functions, with varying vessel speed. Doubling the value of the vessel speed results in halving the duration of that phase, when no overflow losses are considered. The results show that this is indeed the case. It is shown that the sailing empty activity is set at zero, since the hopper is not triggered to continue operating since all the material is already transported from the winning location to the dump location.

Table B.4: Results internal validation test: draghead

Component	Unit	Condition (m/s)	Model value	Analytical value	Succeeded test
Duration loading	hr	0.5; 1.0; 2	0.508; 0.508; 0.508	0.5; 0.5; 0.5	yes
Power loading	kW	0.5; 1.0; 2	3982; 3982; 3982	3982; 3982; 3982	yes
Energy loading	kWh	0.5; 1.0; 2	2022; 2022; 2022	1991; 1991; 1991	yes
Fuel loading	l	0.5; 1.0; 2	2022; 2022; 2022	1991; 1991; 1991	yes
Costs loading	€	0.5; 1.0; 2	2022; 2022; 2022	1991; 1991; 1991	yes
CO_2 loading	kg	0.5; 1.0; 2	2022; 2022; 2022	1991; 1991; 1991	yes
kg CO_2 / m^3	-	0.5; 1.0; 2	0.56; 0.56; 0.56	0.55; 0.55; 0.55	yes
Duration sailing empty	hr	0.5; 1.0; 2	0; 0; 0	0; 0; 0	yes
Power sailing empty	kW	0.5; 1.0; 2	0; 0; 0	0; 0; 0	yes
Energy sailing empty	kWh	0.5; 1.0; 2	0; 0; 0	0; 0; 0	yes
Fuel sailing empty	l	0.5; 1.0; 2	0; 0; 0	0; 0; 0	yes
Costs sailing empty	€	0.5; 1.0; 2	0; 0; 0	0; 0; 0	yes
CO_2 sailing empty	kg	0.5; 1.0; 2	0; 0; 0	0; 0; 0	yes
kg CO_2 / m^3	-	0.5; 1.0; 2	0; 0; 0	0; 0; 0	yes
Duration sailing filled	hr	0.5; 1.0; 2	2.0; 1.0; 0.5	2.0; 1.0; 0.5	yes
Power sailing filled	kW	0.5; 1.0; 2	1000; 1000; 1000	1000; 1000; 1000	yes
Energy sailing filled	kWh	0.5; 1.0; 2	2000; 1000; 500	2000; 1000; 500	yes
Fuel sailing filled	l	0.5; 1.0; 2	2000; 1000; 500	2000; 1000; 500	yes
Costs sailing filled	€	0.5; 1.0; 2	2000; 1000; 500	2000; 1000; 500	yes
CO_2 sailing filled	kg	0.5; 1.0; 2	2000; 1000; 500	2000; 1000; 500	yes
kg CO_2 / m^3	-	0.5; 1.0; 2	0.56; 0.28; 0.14	0.56; 0.28; 0.14	yes
Duration unloading	hr	0.5; 1.0; 2	1.0; 1.0; 1.1	1.0; 1.0; 1.1	yes
Power unloading	kW	0.5; 1.0; 2	5376; 5376; 5376	5376; 5376; 5376	yes
Energy unloading	kWh	0.5; 1.0; 2	5376; 5376; 5376	5376; 5376; 5376	yes
Fuel unloading	l	0.5; 1.0; 2	5376; 5376; 5376	5376; 5376; 5376	yes
Costs unloading	€	0.5; 1.0; 2	5376; 5376; 5376	5376; 5376; 5376	yes
CO_2 unloading	kg	0.5; 1.0; 2	5376; 5376; 5376	5376; 5376; 5376	yes
number of cycles	-	0.5; 1.0; 2	1; 1; 1	1; 1; 1	yes
kg CO_2 / m^3	-	0.5; 1.0; 2	1.49; 1.49; 1.49	1.49; 1.49; 1.49	yes

Internal validation test: TSHD capacity m^3

Table B.5 present the results for duration (h) of the modelled unit tests and analytical calculated functions, with varying TSHD capacity. Doubling the value of the hopper capacity results in halving the number of cycles that are needed to complete the dredging volume, when no overflow losses are considered. The results show that this is indeed the case.

Table B.5: Results internal validation test: draghead

Component	Unit	Condition (m^3)	Model value	Analytical value	Succeeded test
Duration loading	hr	1800; 3600; 7200	1.036; 1.036; 1.036	1; 1; 1	yes
Power loading	kW	1800; 3600; 7200	4232; 4232; 4232	4232; 4232; 4232	yes
Energy loading	kWh	1800; 3600; 7200	4383; 4383; 4383	4232; 4232; 4232	yes
Fuel loading	l	1800; 3600; 7200	4383; 4383; 4383	4232; 4232; 4232	yes
Costs loading	€	1800; 3600; 7200	4383; 4383; 4383	4232; 4232; 4232	yes
CO_2 loading	kg	1800; 3600; 7200	4383; 4383; 4383	4232; 4232; 4232	yes
kg CO_2 / m^3	-	1800; 3600; 7200	1.22; 1.22; 1.22	1.18; 1.18; 1.18	yes
Duration sailing empty	hr	1800; 3600; 7200	1; 0; 0	1; 0; 0	yes
Power sailing empty	kW	1800; 3600; 7200	2000 ; 0; 0	2000; 0; 0	yes
Energy sailing empty	kWh	1800; 3600; 7200	2000 ; 0; 0	2000 ; 0; 0	yes
Fuel sailing empty	l	1800; 3600; 7200	2000 ; 0; 0	2000 ; 0; 0	yes
Costs sailing empty	€	1800; 3600; 7200	2000 ; 0; 0	2000 ; 0; 0	yes
CO_2 sailing empty	kg	1800; 3600; 7200	2000 ; 0; 0	2000 ; 0; 0	yes
kg CO_2 / m^3	-	1800; 3600; 7200	0.55; 0; 0	0.55; 0; 0	yes
Duration sailing filled	hr	1800; 3600; 7200	2.0; 1.0; 1.0	2.0; 1.0; 1.0	yes
Power sailing filled	kW	1800; 3600; 7200	2000; 2000; 2000	2000; 2000; 2000	yes
Energy sailing filled	kWh	1800; 3600; 7200	4000; 2000; 2000	4000; 2000; 2000	yes
Fuel sailing filled	l	1800; 3600; 7200	4000; 2000; 2000	4000; 2000; 2000	yes
Costs sailing filled	€	1800; 3600; 7200	4000; 2000; 2000	4000; 2000; 2000	yes
CO_2 sailing filled	kg	1800; 3600; 7200	4000; 2000; 2000	4000; 2000; 2000	yes
kg CO_2 / m^3	-	1800; 3600; 7200	1.11; 0.56; 0.56	1.11; 0.56; 0.56	yes
Duration unloading	hr	1800; 3600; 7200	1.0; 1.0; 1.0	1.0; 1.0; 1.0	yes
Power unloading	kW	1800; 3600; 7200	6376; 6376; 6376	6376; 6376; 6376	yes
Energy unloading	kWh	1800; 3600; 7200	6376; 6376; 6376	6376; 6376; 6376	yes
Fuel unloading	l	1800; 3600; 7200	6376; 6376; 6376	6376; 6376; 6376	yes
Costs unloading	€	1800; 3600; 7200	6376; 6376; 6376	6376; 6376; 6376	yes
CO_2 unloading	kg	1800; 3600; 7200	6376; 6376; 6376	6376; 6376; 6376	yes
kg CO_2 / m^3	-	1800; 3600; 7200	1.77; 1.77; 1.77	1.77; 1.77; 1.77	yes
number of cycles	-	1800; 3600; 7200	2; 1; 1	2; 1; 1	yes

Internal validation test: volume to be dredged m^3

Table B.6 present the results for duration (h) of the modelled unit tests and analytical calculated functions, with varying volume to be dredged. Doubling the value of the volume to be dredged results in doubling the number of cycles that are needed to complete the dredging volume, when no overflow losses are considered. The results show that this is indeed the case.

Table B.6: Results internal validation test: volume to be dredged (m^3)

Component	Unit	Condition (m^3)	Model value	Analytical value	Succeeded test
Duration loading	hr	1800; 3600; 7200	0.25; 0.51; 1.02	0.25; 0.5; 1	yes
Power loading	kW	1800; 3600; 7200	3982; 3982; 3982	3982; 3982; 3982	yes
Energy loading	kWh	1800; 3600; 7200	1011; 2022; 4044	995.5; 1991; 3982	yes
Fuel loading	l	1800; 3600; 7200	1011; 2022; 4044	995.5; 1991; 3982	yes
Costs loading	€	1800; 3600; 7200	1011; 2022; 4044	995.5; 1991; 3982	yes
CO_2 loading	kg	1800; 3600; 7200	1011; 2022; 4044	995.5; 1991; 3982	yes
kg CO_2 / m^3	-	1800; 3600; 7200	0.56, 0.56; 0.56	0.55; 0.55; 0.56	yes
Duration sailing empty	hr	1800; 3600; 7200	0; 0; 1	0; 0; 1	yes
Power sailing empty	kW	1800; 3600; 7200	0; 0; 1000	0; 0; 1000	yes
Energy sailing empty	kWh	1800; 3600; 7200	0; 0; 1000	0; 0; 1000	yes
Fuel sailing empty	l	1800; 3600; 7200	0; 0; 1000	0; 0; 1000	yes
Costs sailing empty	€	1800; 3600; 7200	0; 0; 1000	0; 0; 1000	yes
CO_2 sailing empty	kg	1800; 3600; 7200	0; 0; 1000	0; 0; 1000	yes
kg CO_2 / m^3	-	1800; 3600; 7200	0; 0; 0.14	0; 0; 0.14	yes
Duration sailing filled	hr	1800; 3600; 7200	1.0; 1.0; 2.0	1.0; 1.0; 2.0	yes
Power sailing filled	kW	1800; 3600; 7200	1000; 1000; 1000	1000; 1000; 1000	yes
Energy sailing filled	kWh	1800; 3600; 7200	1000; 1000; 2000	1000; 1000; 2000	yes
Fuel sailing filled	l	1800; 3600; 7200	1000; 1000; 2000	1000; 1000; 2000	yes
Costs sailing filled	€	1800; 3600; 7200	1000; 1000; 2000	1000; 1000; 2000	yes
CO_2 sailing filled	kg	1800; 3600; 7200	1000; 1000; 2000	1000; 1000; 2000	yes
kg CO_2 / m^3	-	1800; 3600; 7200	0.56; 0.28; 0.14	0.56; 0.28; 0.14	yes
Duration unloading	hr	1800; 3600; 7200	0.5; 1.0; 2.0	0.5; 1.0; 2.0	yes
Power unloading	kW	1800; 3600; 7200	5376; 5376; 5376	5376; 5376; 5376	yes
Energy unloading	kWh	1800; 3600; 7200	2688; 5376; 10753	2688; 5376; 10753	yes
Fuel unloading	l	1800; 3600; 7200	2688; 5376; 10753	2688; 5376; 10753	yes
Costs unloading	€	1800; 3600; 7200	2688; 5376; 10753	2688; 5376; 10753	yes
CO_2 unloading	kg	1800; 3600; 7200	2688; 5376; 10753	2688; 5376; 10753	yes
kg CO_2 / m^3	-	1800; 3600; 7200	1.49; 1.49; 1.49	1.49; 1.49; 1.49	yes
number of cycles	-	1800; 3600; 7200	1; 1; 2	1; 1; 2	yes

Internal validation test: hopper loading degree (%)

Table B.7 present the results for duration (h) of the modelled unit tests and analytical calculated functions, with varying the hopper loading degree. Halving the loading degree results in doubling the number of cycles that are needed to complete the dredging volume, when no overflow losses are considered. The results show that this is indeed the case.

Table B.7: Results internal validation test: hopper loading degree (%)

Component	Unit	Condition (m^3)	Model value	Analytical value	Succeeded test
Duration loading	hr	0.5; 1.0	0.51; 0.51	0.5;0.5	yes
Power loading	kW	0.5; 1.0	3982; 3982	3982; 3982	yes
Energy loading	kWh	0.5; 1.0	2022; 2022	1991; 1991	yes
Fuel loading	l	0.5; 1.0	2022; 2022	1991; 1991	yes
Costs loading	€	0.5; 1.0	2022; 2022	1991; 1991	yes
CO_2 loading	kg	0.5; 1.0	2022; 2022	1991; 1991	yes
kg CO_2 / m^3	-	0.5; 1.0	0.56, 0.56	0.55; 0.55	yes
Duration sailing empty	hr	0.5; 1.0	1; 1	1; 1	yes
Power sailing empty	kW	0.5; 1.0	1000; 0	1000; 0	yes
Energy sailing empty	kWh	0.5; 1.0	1000; 0	1000; 0	yes
Fuel sailing empty	l	0.5; 1.0	1000; 0	1000; 0	yes
Costs sailing empty	€	0.5; 1.0	1000; 0	1000; 0	yes
CO_2 sailing empty	kg	0.5; 1.0	1000; 0	1000; 0	yes
kg CO_2 / m^3	-	0.5; 1.0	0.28; 0	0.28; 0	yes
Duration sailing filled	hr	0.5; 1.0	2.0; 1.0	2.0; 1.0	yes
Power sailing filled	kW	0.5; 1.0	1000; 1000	1000; 1000	yes
Energy sailing filled	kWh	0.5; 1.0	2000; 1000	2000; 1000	yes
Fuel sailing filled	l	0.5; 1.0	2000; 1000	2000; 1000	yes
Costs sailing filled	€	0.5; 1.0	2000; 1000	2000; 1000	yes
CO_2 sailing filled	kg	0.5; 1.0	2000; 1000	2000; 1000	yes
kg CO_2 / m^3	-	0.5; 1.0	0.56; 0.28	0.56; 0.28	yes
Duration unloading	hr	0.5; 1.0	1.0; 1.0	1.0; 1.0	yes
Power unloading	kW	0.5; 1.0	5376; 5376	5376; 5376	yes
Energy unloading	kWh	0.5; 1.0	5376; 5376	5376; 5376	yes
Fuel unloading	l	0.5; 1.0	5376; 5376	5376; 5376	yes
Costs unloading	€	0.5; 1.0	5376; 5376	5376; 5376	yes
CO_2 unloading	kg	0.5; 1.0	5376; 5376	5376; 5376	yes
kg CO_2 / m^3	-	0.5; 1.0	1.49; 1.49	1.49; 1.49	yes
number of cycles	-	0.5; 1.0	2; 1	2;1	yes

B.2. Validation case

Left out, confidential

C

Simulation results

C.1. Vessel speed reduction

This sections presents additional model output for the vessel speed optimisation case. In Figure C.1 the project duration is presented per simulated vessel speed. In Figure C.2 the costs, including the financial implications of the implementation of a carbon dioxide taxation system, are simulated per vessel speed.

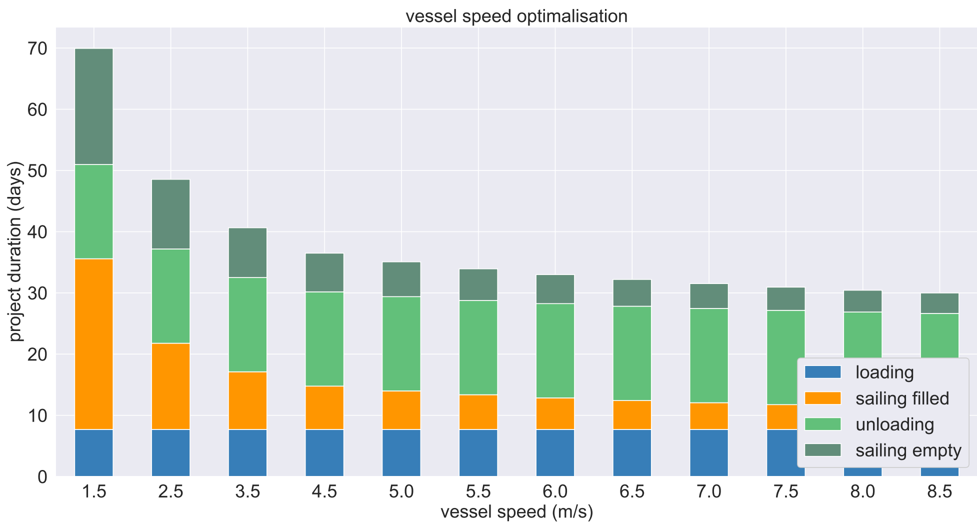

Figure C.1: Consequences of *vessel speed* optimisation in terms of project duration (days) on a *project level*, presenting the duration per cycle event

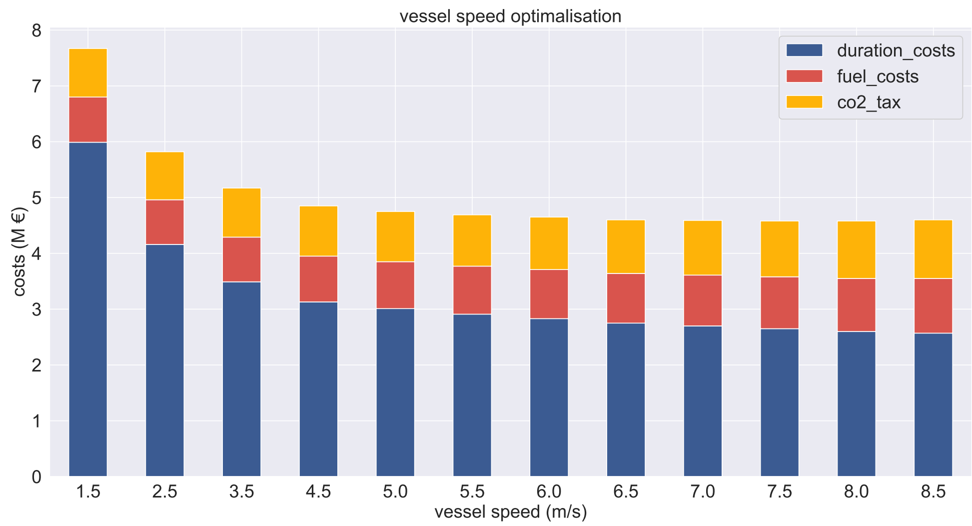

Figure C.2: Consequences of *vessel speed* (m/s) optimisation in terms of project costs on a *project level*, presenting the costs divided in costs for the equipment being on site, fuel and lubricants costs, and CO_2 emission costs; taking a CO_2 tax of 200 € per ton into account

C.2. Trail speed reduction

This sections presents additional model output for the trail speed optimisation case. In Figure C.3 the project duration is presented per simulated trail speed. In Figure C.4 the costs, including the financial implications of the implementation of a carbon dioxide taxation system, are simulated per trail speed.

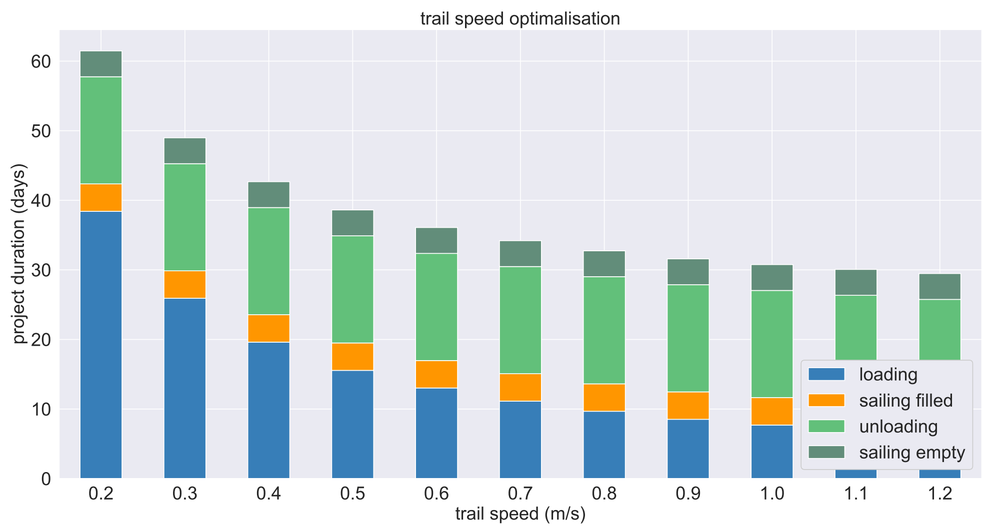

Figure C.3: Consequences of *trail speed* optimisation in terms of project duration (days) on a *project level*, presenting the duration per cycle event

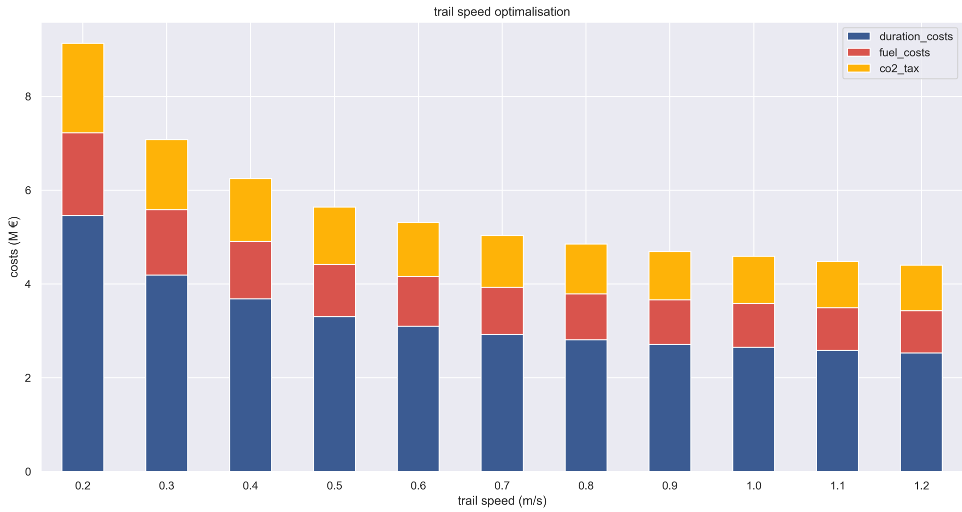

Figure C.4: Consequences of *trail speed* (m/s) optimisation in terms of project costs on a *project level*, presenting the costs divided in costs for the equipment being on site, fuel and lubricants costs, and CO_2 emission costs; taking a CO_2 tax of 200 € per ton into account

C.3. Unloading production

This sections presents additional model output for the unloading production optimisation case. In Figure C.5 the project duration is presented per simulated unloading production rate. In Figure C.6 the costs, including the financial implications of the implementation of a carbon dioxide taxation system, are simulated per unloading production rate.

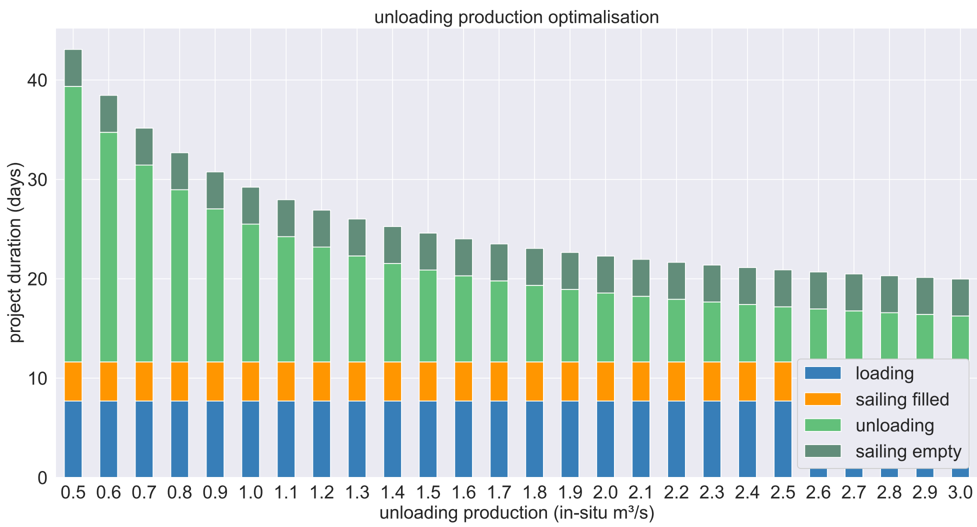

Figure C.5: Consequences of *unloading production* optimisation in terms of project duration (days) on a *project level*, presenting the duration per cycle event

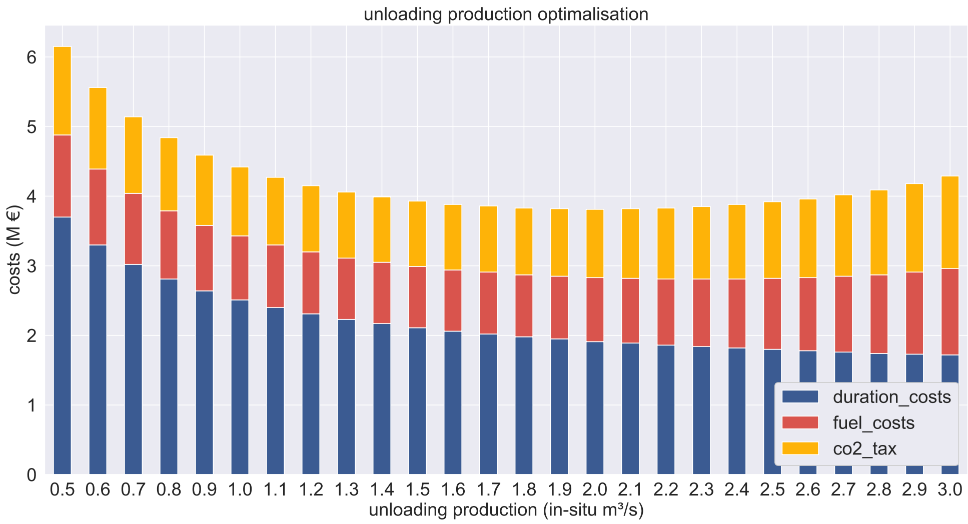

Figure C.6: Consequences of *unloading production* (m^3/s) optimisation in terms of project costs on a *project level*, presenting the costs divided in costs for the equipment being on site, fuel and lubricants costs, and CO_2 emission costs; taking a CO_2 tax of 200 € per ton into account

C.4. Adapting the dredging location

This sections presents additional model output for the adapting the dredging location optimisation case. In Figure C.7 the project duration is presented per simulated dredging depth. In Figure C.8 the costs, including the financial implications of the implementation of a carbon dioxide taxation system, are simulated per dredging depth.

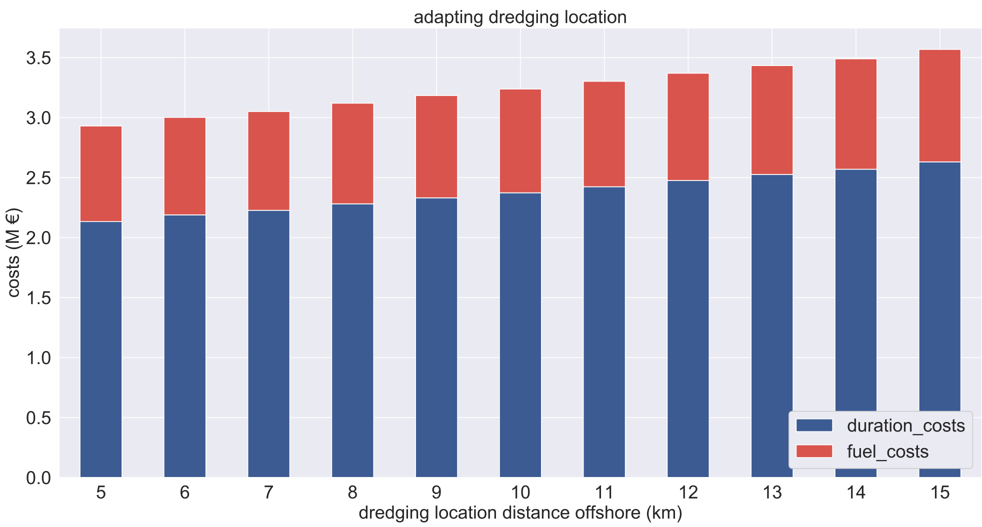

Figure C.7: Consequences of *adapting the dredging location* optimisation in terms of project costs on a *project level*, presenting the costs divided in costs for the equipment being on site and in fuel and lubricants costs

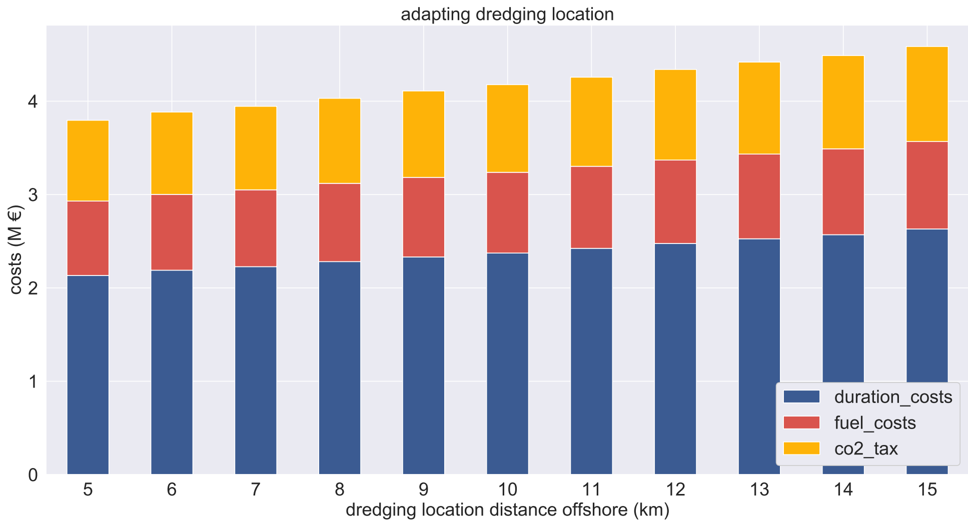

Figure C.8: Consequences of *dredging within -20 m depth contour* optimisation in terms of project costs on a *project level*, presenting the costs divided in costs for the equipment being on site, fuel and lubricants costs, and CO_2 emission costs; taking a CO_2 tax of 200 € per ton into account

C.5. Dumping method

This sections presents additional model output for the dumping method optimisation case. In Figure C.7 the project duration is presented per simulated dumping method. In Figure C.8 the costs, including the financial implications of the implementation of a carbon dioxide taxation system, are simulated per dumping method.

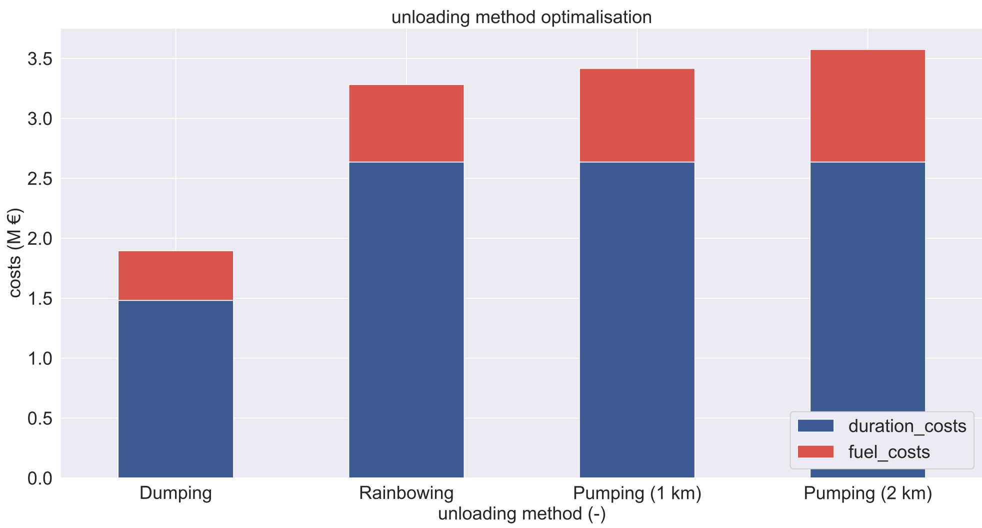

Figure C.9: Consequences of *dumping method* optimisation in terms of project costs on a *project level*, presenting the costs divided in costs for the equipment being on site and in fuel and lubricants costs

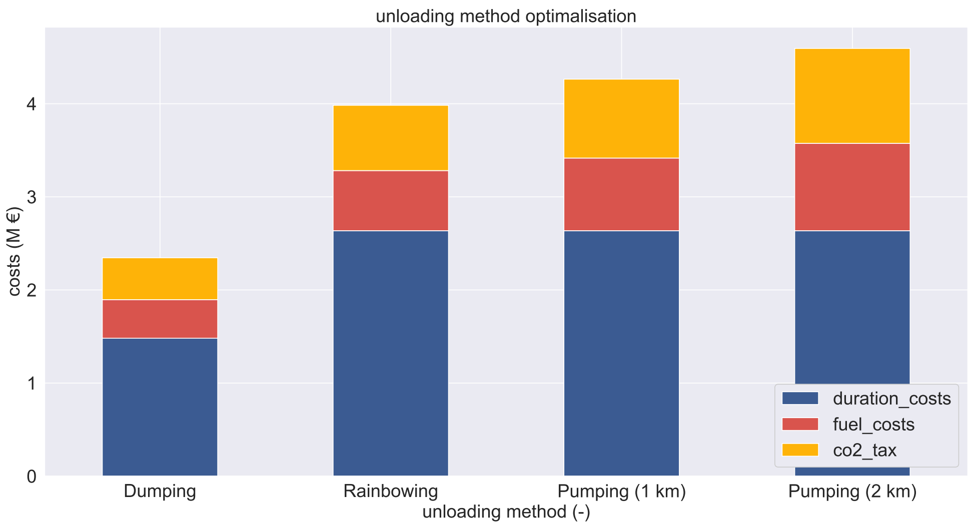

Figure C.10: Consequences of *dumping method* optimisation in terms of project costs on a *project level*, presenting the costs divided in costs for the equipment being on site, fuel and lubricants costs, and CO_2 emission costs; taking a CO_2 tax of 200 € per ton into account

D

Code archive

The set-up of the model is based on an open source package developed by the TU Delft, known as *Open Complex Logistics Simulation (OpenCLSim)*. The package is available on the digital academic repository Zenodo. OpenCLSim is a rule based planning tool for cyclic activities and in depth comparison of different system concepts. Figure D.1 provides a link to the repository where different applications of the tool are demonstrated.

The package developed for this thesis that is working in combination with the OpenCLSim package to generate the TSHD specific output concerning energy consumption and production can be found in Figure D.2. The simulation of the base case project can be found in Figure D.3. The different stages of the validation process are presented in the validation section on the repository, a link can be found in Figure D.4. To conclude, in Figure D.5 a link can be found to the different notebooks of the optimisation cases worked out.

Figure D.1: Link to OpenCLSim package available at the Zenodo repository

Figure D.2: Link to the Github Van Oord repository Afstuderen Vibeke; developed core

Figure D.3: Link to the Github Van Oord repository Afstuderen Vibeke; base case simulation

Figure D.4: Link to the Github Van Oord repository Afstuderen Vibeke; validation simualtions

Figure D.5: Link to the Github Van Oord repository Afstuderen Vibeke; optimisation simulations

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