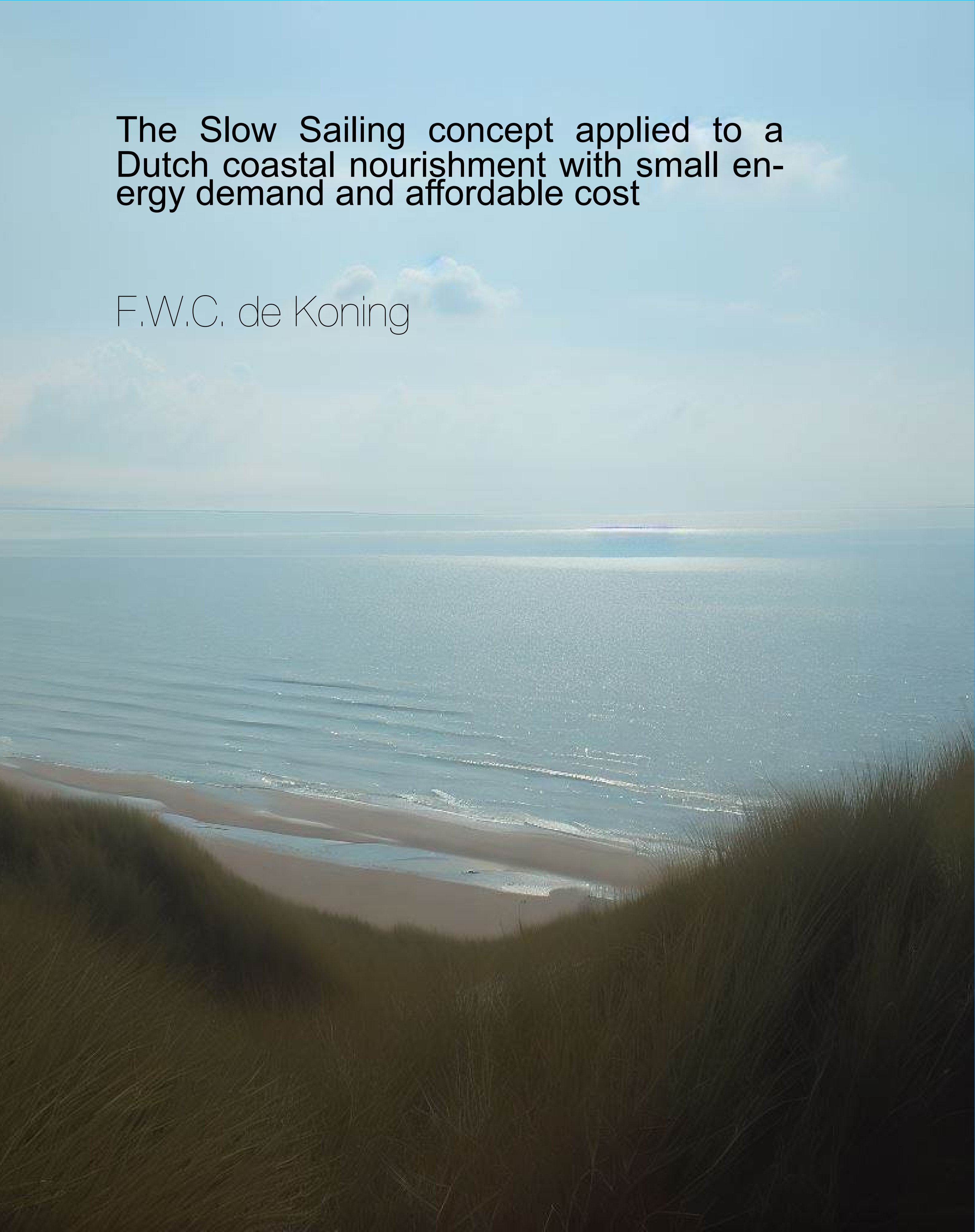
The Slow Sailing concept applied to a Dutch coastal nourishment with small energy demand and affordable cost

F.W.C. de Koning



The Slow Sailing concept applied to a Dutch coastal nourishment with small energy demand and affordable cost

by

F.W.C. de Koning

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Acknowledgements

During the last year, I experienced the final phase of my student career. The master's thesis project was designed and configured to focus on adding scientific knowledge and required me to undergo numerous steps along the way. Throughout this process, I learned and experienced various aspects that helped me grow as a person and gain a better perspective on my interests, strengths, and weaknesses. To achieve this, I assembled a team of committee members who individually and collectively assisted me in improving my skills and progressing through the project.

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F.W.C. (Floris) de Koning
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Abstract

This research focuses on a new system for nourishing the Dutch coast with sand, which utilizes semi-autonomous sailing barges and an electrical crawler to continuously replenish the beach. Yearly, the Dutch government grants contracts to nourish the Dutch coast with volumes around 10.000.000 m^3. The Dutch dune coast protects the low part of the Netherlands against inundation from the North sea. This sand is dredged by Trailer Suction Hopper Dredgers (TSHD) on a depth of 20 m and transported to the coast. This transport causes a CO2 emission of about 190 kilo tonne a year. As emissions are expected to grow with increasing sea levels the Dutch government looks for ways to improve the high-energy demanding strategy that is currently used. Sweco introduced the Slow Sailing, and believes in the energy reducing concept and therefore initiates this further research. The general idea of this concept is to reduce the energy demand and emissions associated with traditional sand nourishment practices by using multiple barges that sail slowly and continuously nourish the Dutch coast. The aim of this research is to concretize this concept, in which feasibility of the system compared with energy, emission and cost calculations are central. To achieve this goal, the Slow Sailing system is compared to the traditional trailer suction hopper dredger, currently used for sand nourishment in the Netherlands. The comparison is based on a scenario in the Northsea. This leads to the main research question: What is the gain in energy consumption, emissions and cost for the Slow Sailing concept compared to classical nourishment strategies? In order to achieve this goal a review of current sand nourishment strategies was conducted. Next, the OpenTNSim model was adapted to perform energy calculations and enable a comparison of energy demands and emissions between the new system and the traditional trailer suction hopper dredger. Finally, a cost evaluation was conducted to compare the cost per cubic meter of sand for a 1.000.000 cubic meter nourishment project at the Egmond aan Zee nearshore in the Netherlands.

Compared to the traditional trailer suction hopper dredger, the Slow Sailing system showed a significant factor 15 decrease in energy demand in the sailing component of the dredging cycle. The Slow Sailing system with barges of 1500 m^3 was found to be the most energy-efficient and cost-effective option, with an estimated project cost of 3.00 euro/m^3, while the TSHD with 4280 m^3 was found to be the cheapest option, with an estimated project cost of 2.55 euro/m^3. In terms of CO2 emissions, the Slow Sailing system emitted significantly less CO2 compared to the TSHD, with a difference of 1000 tonnes CO2+ emission in a one million cubic meter dredging project. Overall, the results suggest that the Slow Sailing system is a more energy-efficient and environmentally-friendly option for sand nourishment of the Dutch coast.

Contents

1

Introduction

1.1. Motivation

The motivation for this project comes from the innovating actions of the Dutch waterboard: Rijkswaterstaat. As there is a constant and growing need for sand nourishments on the Dutch coast in the nearshore and on the beaches, it launched a program for innovation in dynamic coastline preservation (Rijkswaterstaat, 2021). These sand nourishments are done in order to keep the Dutch coastline at the desired safety level. This safety level is called the Base Coastline, basiskustlijn (BKL) in Dutch. The Base Coastline was set as a reference for the Dutch coast and originates from the coastline in 1990 (V&W, 1990). It considers the coastal area from the dunes to the -20m depth contour, called the 'coastal foundation'. This coastal foundation is used as the base area for gross sediment needs of the Dutch coast as sand entering the foundation is expected to stay within its boundaries (Mulder et al., 2011). It is set to protect the Dutch hinterland that houses 9 million people living in areas below sea level, and 70% of the gross domestic product of the Netherlands is being earned in these areas. Due to structural erosion along the Dutch coast that varies over time and space, the cross section profile of the Dutch coast can fall below this base coast line. In which case the Dutch waterboard orders and plans nourishments in order to restore the coastline (Roelse, 2002).

As these nourishments are expected to stay a constant factor in the Dutch water safety the program for innovation in dynamic coastline preservation was set up Rijkswaterstaat (2020). In this program companies are asked to look at new ways and new tools to carry out these nourishments in order to reduce the emissions of these nourishment activities in the coming years. In 2021 the CO2 emissions for all coastal and inland maintenance works related to was 190 kilo tonnes (V&W, 2021). The request for lowering emissions is in line with the European plans and ambitions defined by the European commission in the European Green Deal. It strives to cut 90% of emissions by 2050 for all transport systems and states a specific wish to boost innovation (European Commission, 2021). This includes all marine vessels and there is a distinct focus on automated transport in this transition. Sweco joined the open registration with the Slow Sailing concept in which the sailing speed of the vessels is greatly reduced in order to reduce the energy demand and thus missions of the nourishments.

1.2. Philosophy

The general idea of the Slow Sailing concept is in line with the philosophy of the water engineers at Sweco. In current times projects in the engineering world are carried out with a focus on cost and profit. Projects are worked out at high speed and intensity with less focus on the environment and emissions. Sweco believes that structural problems need structural solutions and the focus should be shifted. This is the case with the nourishments of the Dutch coast. That is why the innovating company Sweco offered two types of systems that can provide a solution to this challenge set by Rijkswaterstaat. Sweco believes it is wise to reconsider more eco-friendly alternatives in case of structural problems. The general philosophy is: why do it fast and with a large impact on the environment if you can also carry out the project in a longer period of time and have a way smaller impact on the environment. This philosophy results in new ways of thinking about the system that is used to nourish the Dutch coast.

1.3. Research objective

The goal of this report is to provide an insight into the different components and intentions of the Slow Sailing concept. Therein, creating a clear and concrete setting in which the systems limitations are shown and the advantages are highlighted. The concretization is performed in calculation of energy demands, emissions and cost that are related to the Slow Sailing concept. In addition, the provided information on these topics is compared to the current strategy to find relative impacts and financial comparisons in case the system would be implemented.

1.4. Other research

This report builds upon first research by Sweco into this subject. The concept has been reported to Rijkswaterstaat and is therefore under review for the first stage of implementation: exploring. This can be seen at the Rijkswaterstaat website, where updates on all current innovations are provided. It is shown under the innovations in coastal care, only available in Dutch. At first the Sweco documents provide broad energy estimates and different system set ups, including sand mining and disposal methods. One, two and three barges are considered that sail 1 km/h from and towards the coast. A basic energy indication was provided, which was based on Rutteman (2021) who showed tidal velocities along the Dutch coast. Other environmental impacts, such as wind, were included as guessed estimates. In addition, Sweco did research into the possibility of semi-autonomous sailing of barges. This means that barges would be equipped with sensors and radars in order to be autonomous, while a control room would be set up in which a person would monitor the barges and progress. This was found to be feasible and cost estimates were provided that are used in Chapter 2.

1.5. Scope and feasibility

As the report builds upon the earlier work done by Sweco a next step is made in concretizing the concept. The research provides energy calculations and emissions estimates as well as a feasibility study based on local wind conditions and tidal velocities. Next to these technical aspects also a financial study is performed next to the technical work. In some cases assumptions are made to complete calculations and as these are made they are explicitly stated. In financial calculations the sources and validity of the sources is also elaborated on.

What is not part of this study is any legal related issues directed at the implementation of semi-autonomous sailing or anchoring in shallow Dutch coastal waters. An idealised scenario will be shown that provides insight into an area of interest at the Dutch coastline. Small practical issues in this scenario are also neglected. This holds for example for windmill placements in the area, other shipping activities, or redirection because of buoys.

1.6. Research questions

Research question	
What is the gain in energy consumption, emissions and cost for the Slow Sailing concept compared to classical nourishment strategies?	

Sub-questions	Chapter
What environment is the system implemented in and how can this be schematized?	2
What components are in an operating Slow Sailing system and how will they interact to create a complete system?	2
How can you analyze the feasibility of the Slow Sailing concept in this area based on local wind and tidal conditions?	3
What are cost components in the Slow Sailing system and how do they compare to classical nourishment strategies?	4

Table 1.1: Research question and sub-questions

1.7. Approach

The method that is followed in this report is shown below in Figure 1.1. It shows that first the system is described in more detail to gain a full overview of components, assumptions and schematizations of the system. After which the feasibility is researched based on the wind conditions provided in the system description. After that different scenario's will be compared to gain insight into different considerations of the system. Comparin the system to a trailer suction hopper dredger.After that sensitivity to different system components is provided, so that different outcomes to used assumptions can be tested. From those results conclusions can be drawn.

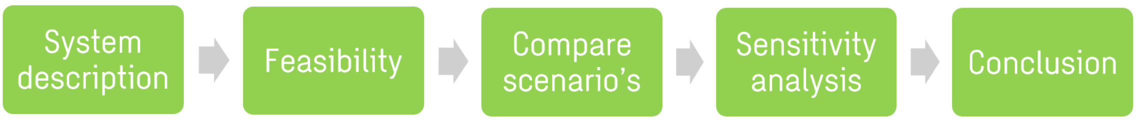


Figure 1.1: Project Workflow

1.8. Report outline

In this report first the system description is presented in Chapter 2. It describes different environmental conditions in the Northsea area. Different nourishment strategies used and researched will also be provided in this Chapter to provide an overview of what the nourishment strategy of the Dutch government is like. After that all system components are shown, system interactions are given and a project proposal is set.

In Chapter 3 the feasibility study is shown for the project based on the local wind conditions. It consist of four parts. First the model OpenTNSim is introduced that is used for the energy calculations and it is shown how the model is adapted to incorporate wind forcing. Secondly, it is shown how this wind forcing affects the steering of the barges in the system and a minimal speed is set for the system. Thirdly, the sailing speed is used to create system aligned with the tidal current. Lastly, the local wind conditions are used to calculate a windfactor that is based on the loaded and unloaded sailing of the barges. It can be applied in calculating project wide energy calculations.

In Chapter 4 the results are presented. The Slow Sailing system shows its results for the energy, emissions and cost. Thereafter, the TSHD energy, emissions and cost is shown. After which both strategies are compared and the sensitivities of certain impacts are shown.

Chapter 5 discusses the results. It includes interpretations of the results and assumptions used. Thereby reflecting on the all aspects of the research.

In Chapter 6 the conclusions are reported. The conclusions are based on the results and the discussion and relate to the research question and sub-questions. After that the chapter provides a broad recommendation section, which shows more ways of implementing the Slow Sailing system and provides insight in research needed before implementation.

2
System description

The system description chapter provides a broad overview of the system in which the Slow Sailing concept will be tested. In this, the first part is focused on the environment and local conditions. The second part elaborates on a dredging project and all available components in the system.

2.1. Environment

This research is focused on the Dutch coast area, the Noord-Holland coast in particular. Along the entire Dutch coast nourishments are done on a yearly basis. The nourishments are executed to mitigate the structural erosion that takes place along the coastline and to help adapt the coastline in order to keep the safety level high despite sea level rise. The nourishments contribute to the coastal safety, but also in maintaining the nature reserves, fresh water supply and recreational possibilities (Rijkswaterstaat, 2021). The spread of nourishments along the coast that have taken place in recent years is shown in Figure 2.13b. It shows the amount of nourishments carried out in the years 2011-2020 in Mm^3 An increased length of the bars in the Figure indicate larger nourishments during this period. Most sand is deposited at the North part of the Noord-Holland province and at the islands in the North at the Waddensea. Research has shown that the need for these sand nourishments in the coming years is is expected to grow due to the sea level rise (Rijkswaterstaat, 2021).

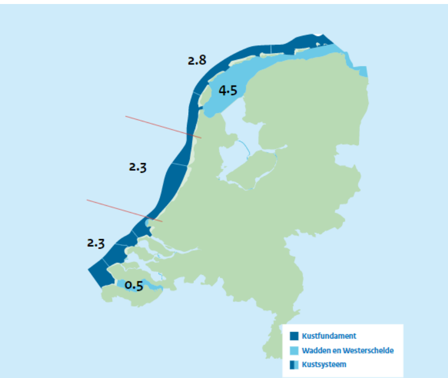


Figure 2.1: Sediment need for Dutch coast subsystems in Mm^3 per year (Rijkswaterstaat, 2021)

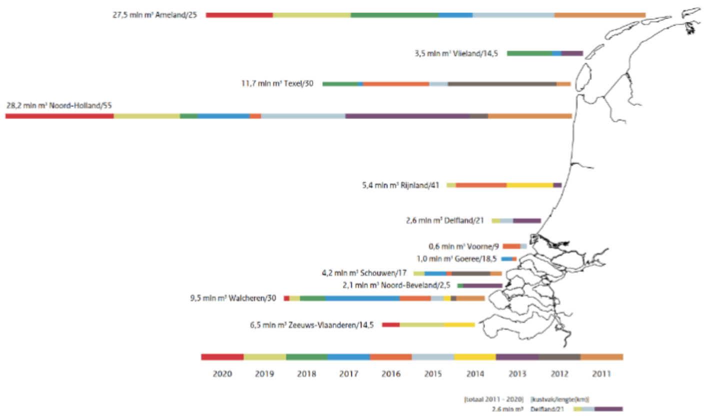


Figure 2.2: Nourishment distribution along the dutch coast 2011-2020 in Mm^3

The Dutch coastal safety policy is based on the Bruun rule. It forms the substantive basis for nourishment policy in the Netherlands (Rijkswaterstaat, 2020). This theory assumes that the shape of the coastal profile remains the same with sea level rise (Bruun, 1962). As a result, the equilibrium profile moves landward with the shallow coastal zone losing sand (resulting in coastal backwash) and the deeper coastal zone "gaining" sand (see Figure 2.3). There is debate in scientific literature about the Bruun rule. Several comments can be made about its validity, but it is also concluded that the rule is of value because of its simplicity and that there is no universally valid alternative (Rosati et al., 2013). By adding sand with nourishments, the initial profile is increased, and the profile remains at its equilibrium depth despite sea level rise. As a result, less sand is lost from the shallow coastal zone, which limits or stops the landward retreat of the shoreline, see Figure 2.4.

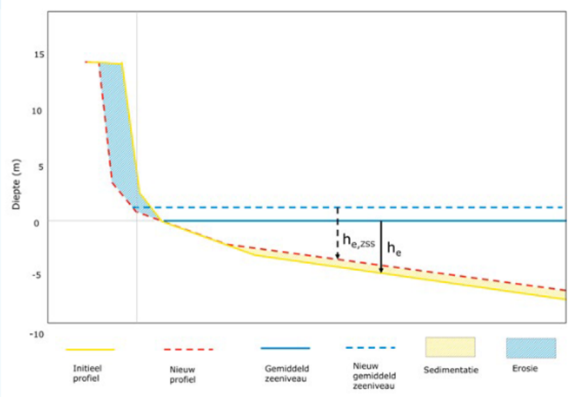


Figure 2.3: Erosion of initial profile with sea level rise without nourishment

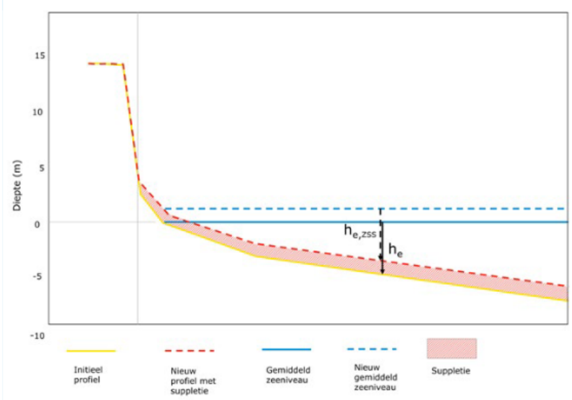


Figure 2.4: Adaptation of profile with sea level rise with suppletion

As during the last decades the yearly sea level rise has been 1.86 mm/year (Rijkswaterstaat, 2020), sediment has to be brought into the system on a regular basis. Also, the creation of the Waddensea by closing of the Zuiderzee has led to sediment escaping the system and settle in the Waddensea. These factors have led to continuous nourishments over the years and lead to more nourishments in the future. As the projections for the rate of sea level rise are uncertain, Rijkswaterstaat provides in its Kustgenese 2.0 estimates of sediment needs based on different rates of sea level rise. These are summarized in Table 2.1. It shows sediment need for the dutch coastal area in 2100 based on different sea level rise scenario's. It is important for Rijkswaterstaat to monitor the evaluation of the sea level rise as the Netherlands is in a highly vulnerable coastal zone for potential consequences of sea level rise (Nicholls and de la Vega-Leinert, 2008).

Sea level rise [mm/year]	2	4	6	8	10
Sediment need [million m^3/year]	12.4	20.4	27.9	35.5	50

Table 2.1: Sediment need of dutch coastal foundation 2100 (Rijkswaterstaat, 2020)

Currently, a large part of the problems for adaptation of measurements to sea level rise is the large uncertainty in the predictions. In Figure 2.5 it can be seen that the projections made by dutch research institute Deltares are also including large uncertainty and are only very rough estimates following different scenario's. The reason for this uncertainty is that there is no consensus about what the sea level rise will be to the year 2100.

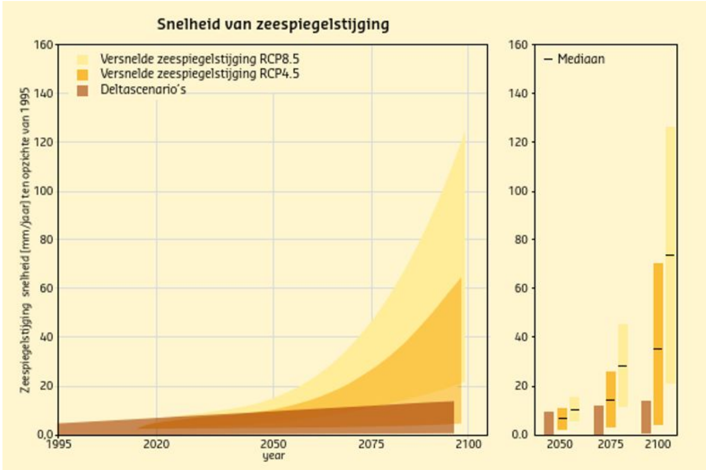


Figure 2.5: Different sea level rise projections by Deltares, (Haasnoot et al., 2018)

2.1.1. Bathymetry

Along the coast the depth profile has a typical build up as shown in Figure 2.6. It is composed of a dune section at the shore, a beach section adjacent to the dunes that ends at the mean sea level. Below the mean sea level line the shallow foreshore zone starts in which mostly waves are of influence and some sandbars might be present. In the deeper foreshore starting at NAP -8 the profile is mostly stable under an angle of 1:200 to 1:1000 until the -20m depth line at which the continental plate starts.

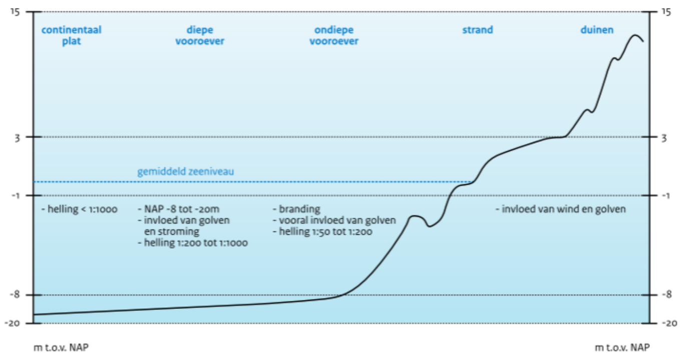


Figure 2.6: Typical dutch coastal depth profile (Rijkswaterstaat, 2020)

Grain size distributions

The overall particle size of the coastal foundation in the dutch coastal area is in the range of 100 - 500 μm. With a more coarse distribution in the surf-zone, where the waves break and more finer sediments towards the open sea (Van Straaten, 1965). In order to provide stable sand conditions the aimed medium grain size of nourished sand is in the range of 250 - 350 μm (Van Duin et al., 2012). In some cases the placement of sand in the nearshore can actually lead to coarsening of the local sediment distribution as for example in case of the Sandmtoor shown in Huisman et al. (2014).

2.1.2. Tidal current

Tides in the North Sea are caused by the gravitational forces of the Moon and the Sun, as well as the rotation of the Earth. The tidal signal in this region are semi-diurnal, meaning that there are two high tides and two low tides every day. The magnitude of the tidal velocity that is related to the tidal wave can vary depending on a number of factors, including the phase of the Moon, the time of year, and local weather conditions (Bosboom and Stive, 2015). The tide along the dutch coast is mostly influenced by the M2 tidal constituent. It has a period of 12.25 hours or 12.4 hours in a decimal notation. It flows along the coastline starting from the Southwest in Zeeland and flows along the coast into the Waddensea-inlets and back. For most places along the dutch coastline this means that the tidal velocity (the horizontal velocity of the water) can be schematized to a sinusoidal velocity signal. The velocity, first, increases up to a maximum and decreases to a minimum after. On a map of the Netherlands it can be visualized as a wave that moves from the Southwest to the northeast and back over a period of 12 hours and 25 minutes. The tide propagates in an anti-clockwise direction around the amphidromic point in the North sea between the Netherlands and England, shown in Figure 2.7. The complete tidal velocity signal is made up of multiple tidal constituents (Gerkema, 2019). While each of these constituents has a different impact on the tidal velocity, in this case they are approximated as having a symmetric effect on the water's motion. This means that the current flows in both directions with equal magnitude during each cycle of the tide, resulting in a net zero flow over the entire tidal cycle as shown in Figure 2.10. This is a simplification of reality as it ignores both the neap/spring cycle as the asymmetry of the horizontal velocity signal.

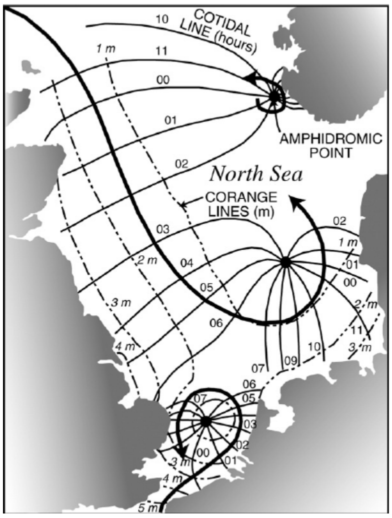


Figure 2.7: Amphidromic points in the Northsea (Kvale, 2006)

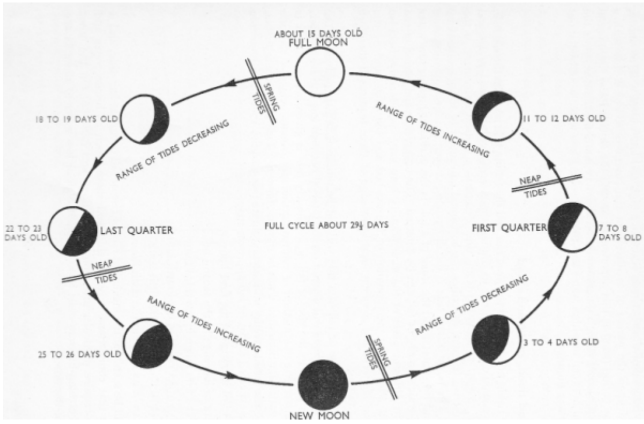


Figure 2.8: Neap and spring tidal cycle

The spring neap cycle occurs due to the combined gravitational effects of the Sun and the Moon. When the Sun and Moon are aligned, as during a new moon or full moon, their gravitational forces reinforce each other, intensifying the tidal bulges. Conversely, when the Sun and Moon are at right angles to each other, as during the first quarter or third quarter phases, their gravitational forces partially cancel each other out, resulting in less pronounced tidal bulges Bosboom and Stive (2015). This results in differentiating tidal velocities during the months, which is simplified to one constant velocity magnitude for all situations.

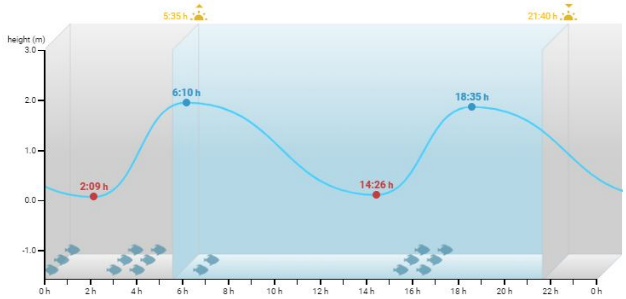


Figure 2.9: Tidal signal IJmuiden (tides4fishing, 2023)

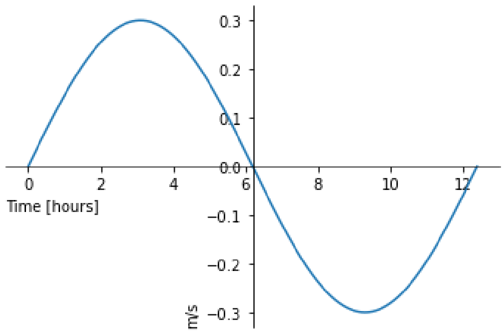


Figure 2.10: Sinusoidal horizontal tidal velocity approximation

The asymmetry in the tidal motion is due to the influence of multiple tidal constituents, this leads to a shifted sinusoidal wave as can be seen in 2.9. The effect of this is that the time from high water to low water is not the same resulting in residual flow. At IJmuiden this residual flow carries a drifting ship a little to the North each cycle. This deviation is ignored in this study.

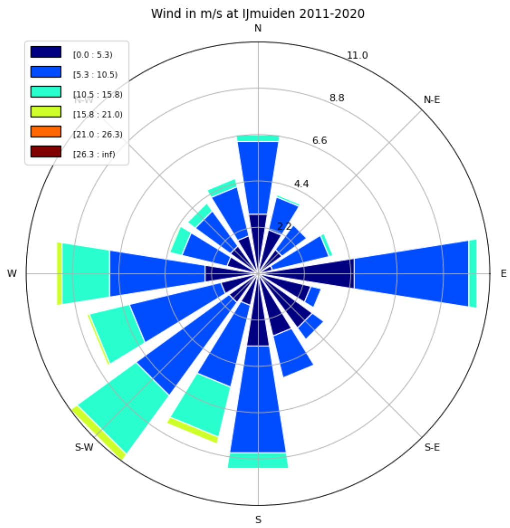
2.1.3. Wind climate at the Northsea

The wind is one of the governing factors in the Slow Sailing project. The Northsea and the Netherlands have a wind climate that is related to their geographical placement. The main wind direction is the Southwest direction as can be seen in Siegismund and Schrum (2001). The Northsea is already used for windmills and turbines as the relative shallow water and favourable climate are stimulating factors as the dutch government strives for all green energy sources in 2050 (Rijksoverheid, 2023). In order to use accurate estimates for the wind speed and direction, wind data from the last 10 years is analyzed. The wind measurement station along the coast in IJmuiden is used. This data gives the average wind speed the last 10 minutes of every hour of the day for that period. The wind speeds are corrected for the measurement height of the wind station at 10 m to a height of 5 m above the water. As wind is slowed down significantly at lower altitudes as shown in ITTC (2021). This results in wind speeds that are actually present at the barge. The conversion of wind speeds to speeds present at the barge is given in Equation 2.1.

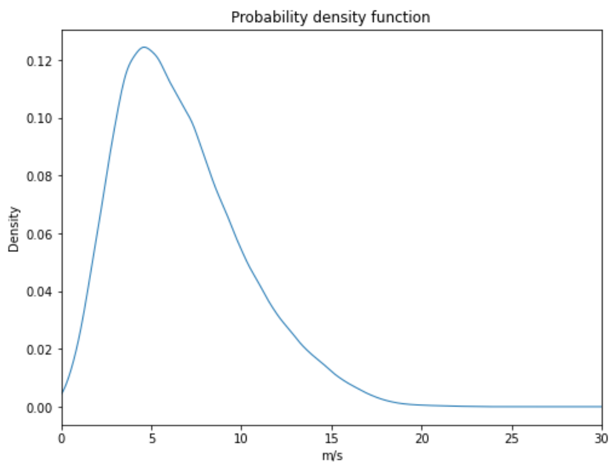
$$V_{WTref} = V_{WT}(\frac{Z_{ref}}{Z_a})^{1/9} \tag{2.1}$$

In which:
V_{WTref} = true wind speed at reference height [m/s]
V_{WT} = true wind speed at measured height [m/s]
Z_{ref} = reference height [m]
Z_a = height of measurement [m]

This can be converted to a wind rose in which the windspeeds and directions are presented as well as a probability density function that represents different appearance rates of windspeeds.



(a) Wind rose IJmuiden 2011-2020



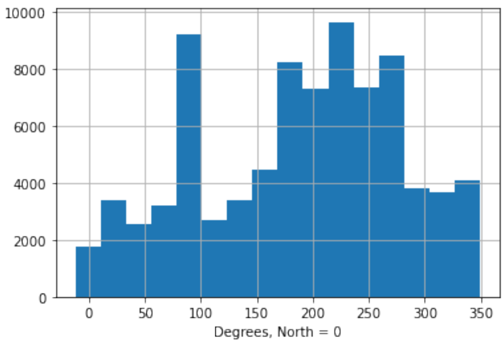
(b) PDF wind speeds IJmuiden

From the data of 2011 to 2020 the maximum measured wind speed was 96.4 km/h at the reference height of 5 m. 50 % of the time the wind was higher than 22,8 km/h, 4 BFT. The data collected is from a 10 year period, therefore the distribution is assumed to be good representation for the variability during

Beaufort	1	2	3	4	5	6	>6
Percent	2	13	22	30	19	11	4
Cumulative	2	15	37	67	86	97	100

Table 2.2: Wind speed distribution in Beaufort, IJmuiden 2011-2020

the year, although the maxima over a longer period are expected to be higher.



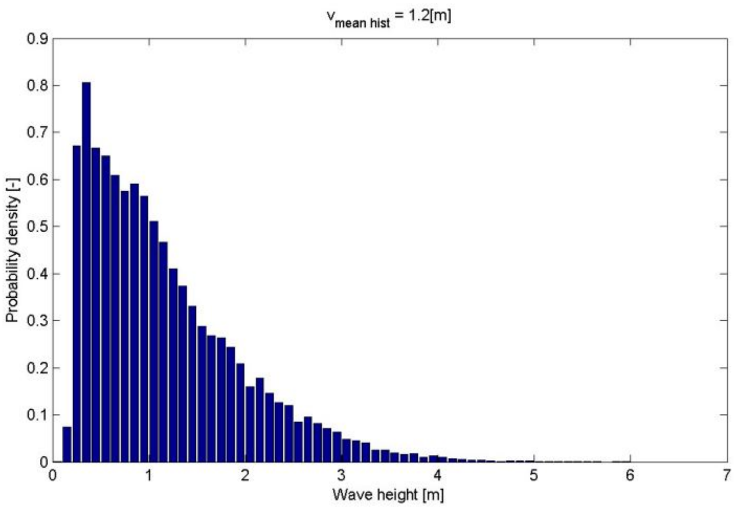
(a) Wind direction histogram IJmuiden 2011-2020

Degrees	Direction	% of time	Degrees	Direction	% of time
0	N	2	180	S	9.5
22.5	NNE	4	202.5	SSWt	8.5
45	NE	3	225	SW	11
67.5	ENE	3.5	247.5	WSW	8.5
90	E	10.5	270	W	9.5
112.5	ESE	3	292.5	WNW	4.5
135	SE	4	315	NW	4
157.5	SSE	5	337.5	NNW	4.5

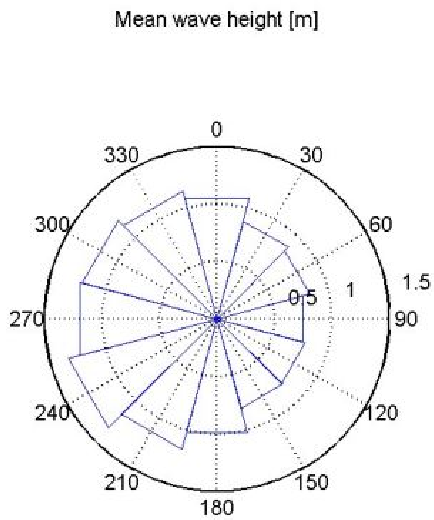
(b) Table presentation of wind direction distribution IJ-muiden 2011-2020

2.1.4. Wave climate on the Northsea

In the Northsea waves of different sizes and origins are present. Besides the tidal wave entering the sea also wind waves are present. These wind waves can be built up in the entire Northsea and come into the dutch coastal foundation being fully grown. Wagenaar and Eecen (2009) shows a wave distribution function for the waves at the coast in front of IJmuiden and in addition also the wind direction distribution is provided. The mean wave height is 1.2 meter and the mean wave direction is Southwest. This distribution is much alike the wind distribution, as most part of the waves are formed directly by wind (Bosboom and Stive, 2015). This study mostly focuses on the impact of wind and the direct impact of waves is ignored. In this study this means that the workability projections made in Chapter 3 are based solely on the wind conditions.



(a) Wave distribution IJmuiden (Wagenaar and Eecen, 2009)



(b) Wave direction distribution IJmuiden

2.2. Dredging activities

The dredging activities section provides the currently used nourishment techniques and the equipment that is currently used to carry out the nourishments.

2.2.1. Nourishment techniques

Different methods are used in order to execute the nourishments. The goal of all methods is to directly influence local sand profiles to protect the hinterland. After the nourishments are finished, the natural processes ensure that the sand is distributed in the system.

Beach nourishment
Until 2000 most nourishments at the dutch were done in the form of beach nourishments (De Sonneville and Van der Spek, 2012), and still this technique is used in places where sand is required directly at the beach (Rijkswaterstaat, 2020). In this technique the sand is directly deposited onto the beach above the mean low water level line and under the dunes, the sediment is brought in by a dredging vessel that unloads with pipelines or valves (Roelse, 2002). It directly increases the beach width and dunes can grow fast as the wind can easily transport the sand, by so called aeolean transport. It is a relatively costly nourishment technique as the sand has to be brought onto shore by pipeline disposal and it has to be distributed at the beach by machinery (Arcadis, 2017).

Nearshore nourishment
The most used nourishment strategy in the Netherlands is currently nearshore nourishments as advised in Van der Spek et al. (2007). In the execution of nearshore nourishments sand is disposed directly in the sea at a depth of 5-8 meters in the shallow foreshore. The exact depth depends on local conditions and needs (Grunnet and Ruessink, 2005). The direct disposal in the sea is cost effective as less equipment and time is needed in the dredging cycle.

Channel nourishment
In the Westerschelde and in the Waddensea also tidal channel nourishments are carried out. In the active tidal channels gullies are often located close to shore. Underwater replenishment on a gully wall has therefore been applied, with the aim of keeping the gully out of shore and possibly providing beach nourishments with a supporting sand body (Van der Spek et al., 2007).

New nourishment techniques
In Rijkswaterstaat (2020) the dutch government discusses the use of new nourishment techniques that are piloted or already in use. Examples described are: deep foreshore nourishments, mega nourishments and nourishments in the outer delta. The deep nearshore nourishments focus on the disposing sediment under the -8 NAP line. In this area also sandbars can be present as shown in Deltares (2020). In 2017, 1 million m^3 of sand was nourished on the deep foreshore. The construction depth was approximately NAP -10 m and the height of the nourishment was 3 m. The objective of the deep foreshore nourishment is the maintenance of the shoreline. The morphological development is monitored and evaluated in the program for management and coastal maintenance (Lodder et al., 2020).

The Sandmotor is a method of adding an excess amount of sand to the coastal system and it is also called a meganourishment. The sediment is then redistributed by natural flow processes. This sand leads to temporary expansion of the coast and contributes multiple functions and values, such as protection against flooding, recreation, nature or knowledge development. Therefore, the concept can vary in terms of design, volume, and location. In 2011, a pilot Sandmotor was constructed for the Delfland coast by adding 19.5 million m^3 of sand in situ (Oost et al., 2016).

Adding sand to the outer delta through suppletion intervenes on the scale of the sea system and utilizes the natural processes on that larger scale. This enables sand losses in the coastal foundation to be nourished before they become a problem for Waddensea island's coastal maintenance (Rijkswaterstaat, 2020). In 2018-2019, a pilot suppletion with a volume of 5 million m^3 of sand was added to the outer delta of the Ameland Sea as part of the Kustgenese 2.0 project. This pilot suppletion contributes to the growth of the coastal foundation with sea level rise and to the acquisition of system knowledge about the morphology and ecology of sea inlets. Additionally, the pilot provides insight into the design, scalability, and feasibility of nourishments on the outer delta.

Sand placement and shape

In the specific case of a nearshore nourishment in the Netherlands, the nourishments are most at the seaward side of the outer bank (Van der Spek et al., 2007). In addition to being, cost-effective it also brings morphological advantages. It prevents the pre-existing bars from migrating seaward (Van Duin et al., 2004) observed that the bars not only move shoreward, but also increase in height. As waves break at the shoreface nourishment, the wave climate becomes calmer shoreward of the nourishment. The wave-driven longshore current is thus diminished, leading to the settling of sediment along the lee side. However, downstream of the nourishment, this can cause erosion since alongshore sediment transport is hindered. Also, the wave shoaling over the nourishment results in onshore sediment transport. In Egmond aan Zee as an example, cross-shore processes are estimated to deliver the sediment to the coast in 5-10 years, assuming the nourishment is placed 700 meters offshore. In the absence of bars Van der Spek et al. (2007) recommends placing the shoreface nourishment as close to the shore as possible. It is possible to adjust the position and form of the actual nourishment to enhance or decrease its erosion rate. Placing multiple disposal spots adjacent to one another could result in the creation of shapes, such as a bar. Such a shape can directly influence its erosion rate, with waves and currents interaction being different, depending on the specific shape employed (Huisman et al., 2019).

2.2.2. Equipment

In order to fulfill the dredging works equipment is used that can transport the sediment from a sand winning location to the shore, where it than can be either directly disposed onto the seabed or indirectly placed in the nearshore or on the beach. In all cases the typical dredging equipment for the nourishment works are Trailer suction hopper dredgers (TSHD). These are all inclusive dredging vessels that can sail towards the winning area freely, use their on board dredge pumps to fill the designated area on board and sail loaded towards the shore location in which the material is needed (Arcadis, 2017). The disposal method can vary based on the needs. The first option is in the nearshore opening of the bottom doors. The second option is rainbowing. In rainbowing the sediment is disposed with an onboard pump, in which the material shoots out towards the sea. The advantage of this method is that the vessel is not needed to be at the exact location where the material is needed. The third option is pipeline disposal, in which a pipeline is placed from the shore and connected to the vessel. The sediment is pumped through the pipeline on the shore where it is distributed along the beach. An example can be seen in Figure 2.14.

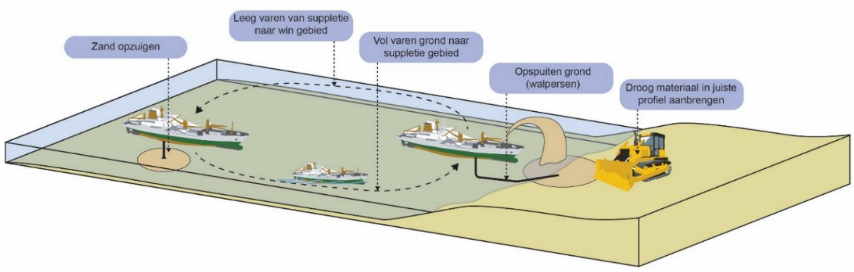


Figure 2.14: Overview dredging cycle including pumping sand ashore (Arcadis, 2017)

2.3. Project

This section provides an overview of the project and its components will be used to compare the Slow Sailing system to the traditional TSHD nourishment strategy. It includes area selection, equipment presentation and interaction.

2.3.1. Area selection

In order to chose a location for the disposal of sand the overall need for sand along the dutch coast is considered. As shown before in Figure 2.1 the need along the Noord-Holland coast is greatest in the North and in the Waddensea islands. For now Egmond aan Zee is chosen as the location that will receive a nourishment. In this case a nearshore nourishment is pictured in front of Egmond aan Zee as can be seen in Figure 2.16. The nearshore nourishment will be available for split barges, so no depth restrictions are needed. The sand winning location is within the area that is appointed by the dutch government as sand-winning area. This area is shown in Figure 2.15. This is the area seaward of the NAP+20 line and within the 12 mile border. The concept of Slow Sailing can be used along the whole coast. The above described location is used as an example.

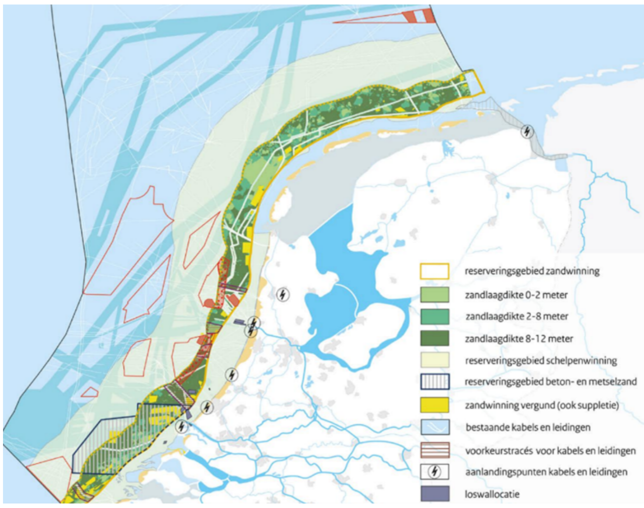


Figure 2.15: Sand winning area along dutch coast (Rijkswaterstaat, 2022)

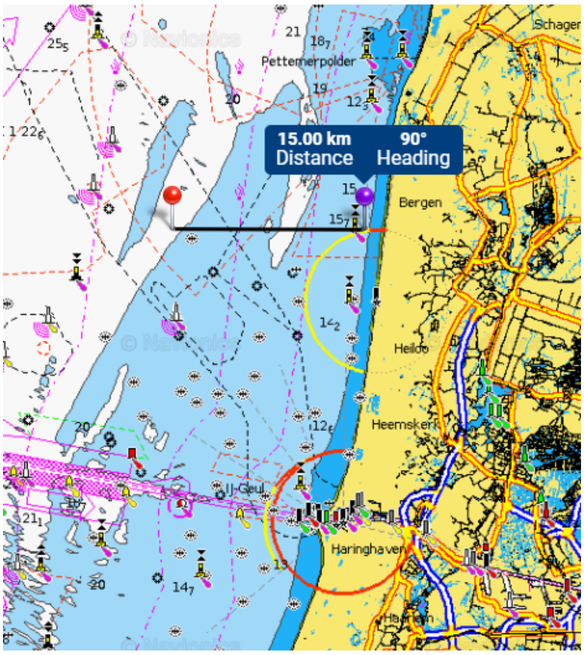


Figure 2.16: Pin at win and disposal location (Navionics, 2022)

2.3.2. Dredging cycle Slow Sailing

The barges will operate in a proper set up that is adjusted to create a maximum efficiency of the system. This means that in the complete cycle all components will be aimed and timed to work in a continuous system, that is aimed to nourish the coast constantly. The barges are expected to operate fully until a maximum of 6 Beaufort or 13.8 m/s. If the wind is increased the ships will find a place along the path in which they will anchor, however if the wind is more than 8 Beaufort or 20.7 m/s the ships must return to a port. An operational system with three barges is logical, since one will be filled, the second will sail to the coast and the third will sail back. Nevertheless other numbers of barges or sailing cycles are also possible. The essence is in the adaption to the tidal cycle of 12.25 hours.

Figure 2.17: Three barges, each in a different phase of the dredging cycle

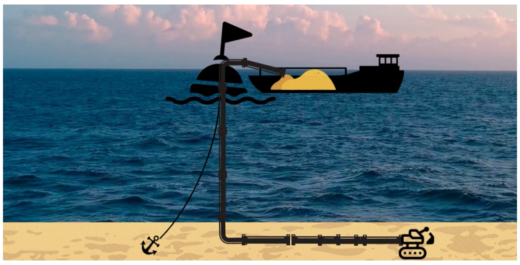


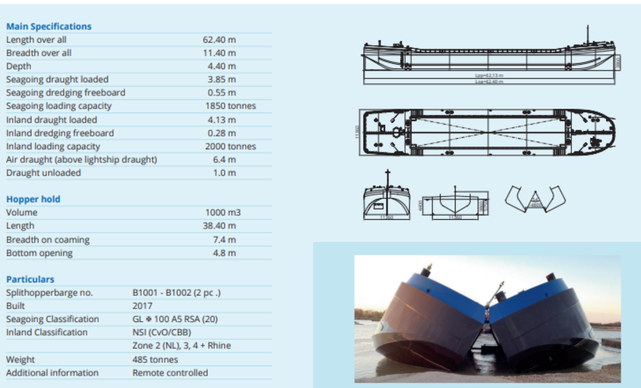
Figure 2.18: Schematization of crawler operation filling a barge

2.3.3. System components

The concept is an integral system that decouples some of the functionalities that are needed in order to perform a dredging project.

Barge

As a starting point for the system components a vessel is chosen that can transport sediment and has no other complicated functionalities. Therefore, a so called 'barge' is the starting point as the vessel. Barges come in multiple sizes and versions, but overall they are standard vessels that can carry various loads and can be classified for different types of waters. As smaller barges will need different requirements than seagoing barges the aim of the barges is specified. In this report the focus is on seagoing barges that have a restricted navigational area. This means that they can sail at sea and serve the coastline, but cannot cross oceans. This is chosen as different barge sizes and seagoing classes come with different costs and this was shown in CIRIA (2009) to be the size most comparable to earlier proposed barge sized by Sweco. As the barges are used for carrying loads, these loads can also be entered and disposed differently depending on the type of barge. A split-barge is considered for this project. The barge can open its bottom to dispose its load as shown in Figure 2.21. This is chosen as this disposal method is the fastest and requires very little energy compared to other strategies. The downside of this method is that a certain depth is needed under the barge to dispose. It is assumed that in the nearshore in this project the depth is sufficient.



Main Specifications	
Length over all	62.40 m
Breadth over all	11.40 m
Depth	4.40 m
Seagoing draught loaded	3.85 m
Seagoing dredging freeboard	0.55 m
Seagoing loading capacity	1850 tonnes
Inland draught loaded	4.13 m
Inland dredging freeboard	0.28 m
Inland loading capacity	2000 tonnes
Air draught (above lightship draught)	6.4 m
Draught unloaded	1.0 m
Hopper hold	
Volume	1000 m3
Length	38.40 m
Breadth on coaming	7.4 m
Bottom opening	4.8 m
Particulars	
Splithopperbarge no.	B1001 - B1002 (2 pc .)
Built	2017
Seagoing Classification	GL ✠ 100 A5 RSA (20)
Inland Classification	NSI (CvO/CBB)
	Zone 2 (NL), 3, 4 + Rhine
Weight	485 tonnes
Additional information	Remote controlled

Figure 2.19: Splitbarge example (BaarsBV, nd)

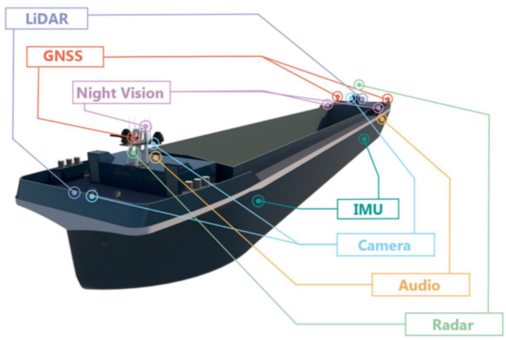


Figure 2.20: Conversion overview barge (Sweco, 2022a)

Semi-autonomous

In opposition to the conventional barges the Slow Sailing concept benefits from some alteration to this classical barge. As a starting point the concept is aimed to provide constant nourishments throughout the year. That implies that the number of hours that the barges are in use is large and that the action on board is relatively small. This means that a change that requires less personnel onboard will make a big difference in cost. That is why an option for a remote controlled barge fits well in this concept, especially when multiple barges are considered in a system. Sweco inquired this option and found it to be workable, introducing the semi-autonomous barge (Sweco, 2022a). That is a remote controlled barge that sails autonomously and controls its own sailing speed and path. It is not fully autonomous as it is monitored at shore. The remote control can control multiple barges at once and this is also advantageous cost wise. More barges means smaller personnel cost per barge. In further notice the term barge is used to refer to the semi-autonomous barges, unless stated otherwise.

These semi-autonomous barges will need to be custom made for the project. In general this study builds on provided data given traditional barges, but in building a new barge for this purpose some other design options might eventually be adjusted as well. As the Slow Sailing concept focuses on continuous nourishments of the coast, all year long, the barges can be build in accordance to this project. This also means, that the hotel options in the barges can be removed to to acquire more space for load and changing the cost of the barge. These other changes, besides the barge being semi-autonomous are not considered further in this study.

Sand mining
The winning of sediment is done by an electric powered crawler that travels over the bottom of the North Sea. The so called 'subdredge' is yet in use in the United States, but has not been tested for use on the North sea. It is available in multiple versions and can be selected to meet requirements. The information disclosed with the subdredge gives a discharge of 1370 m^3/hour with a power use of maximum power capacity of 600 kW. The crawler is electricity powered and needs to be connected to the shore or to nearby windmills. In an alternative case the crawler can be made to use fossil fuels for convenience. However, this is not the desired outcome and thus the electricity pricing is used. It is assumed that the crawler has sufficient driving power to move at the desired speed despite the friction of the pipeline. Also, it is believed that the orbital velocity from waves is not hindering the crawler.

Pipeline
The crawler is connected to a pipeline that is 200 meter long and transports the sand-water mixture towards a fixed point that is anchored to the seabed. The pipeline will lay down at the seabed for most part and come up to the shore underneath the buoy. The reason the pipeline is not floating, is because the waves are assumed too much of a hindering factor in that case.

Coupling system
The anchor spot must be fixed sufficiently as the ships that are filled during part of the cycle will be fastened to this anchor. The pipeline will come out of the water at the surface and will be brought onto the barges to fill them with sand-water mixture. The exact method for the coupling system is not yet developed and will need attention in a later phase of the implementation of the concept. Similar systems are used by TSHD to couple a pipeline in the nearshore. The pipeline transports the sand to the beach. It is also uses by oil tankers at sea to fill the tanker with oil from a storage point. This knowledge can be used to develop a coupling system for the Slow Sailing system.

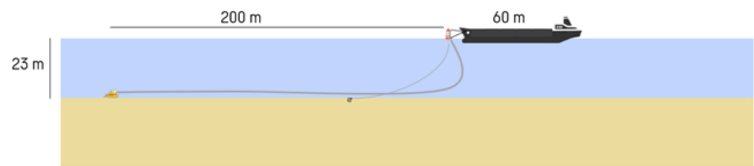


Figure 2.21: Schematic overview anchoring and filling of a barge

2.3.4. System interactions

An overview of the possible manoeuvres and actions a single barge will undergo while in use for the Slow Sailing system. All barges that will be used in the system will be made for use and are therefore assumed to be constantly working on the nourishments of the dutch coast. So, these barges will not be placed to work in other projects.

Sailing to project
Barges will sail towards the winning area. The split barge can be opened to let water into the barge to reduce the influence of wind if advantageous. This step is included as part of the integral moves. In the dredging and project cycle the sailing towards and from the port will not be considered furthermore.

Filling the barge
At the fixed winning location the barge will be attached to the anchored buoy and filled with sand. The barge will be filled with sand particles that are expected to reach the same void ratio as a standard TSHD would reach of 0.4 and an filling rate of 90%, resulting in 10% overflow (Miedema, 2013).

Sail towards disposal location
After the barge is filled it will head towards the disposal location. Underway, the barge is influenced by environmental conditions, but it will be steered and timed so that it will end up in the right place.

Disposal
At the nearshore location the barge will open its bottom doors and release the material. For the nearshore location it is important that there will be sufficient depth to cover under the bottom the barge. Otherwise, it might sail into trouble. The under-keel clearance for now is 5 meters. The location of the ships will be predefined in the route.

Sail back
For the sailing back the same accounts as for the sailing towards the winning point. In execution the decision can be made to fill up the barge to the water level surrounding the barge with the disposal or it can be chosen to let no water into the barge. This decision can be made based on local wind conditions at the time, if the wind is assisting the barge in its path the barge can be left unfilled and when the wind is from an unfavorable direction the barge is filled with water.

Anchoring
As the conditions are too heavy the barges can anchor to prevent the barges from having to sail back and forth to the port. For now, it is assumed that the barge can anchor in any position it is in the cycle. However, in the Netherlands it is currently not allowed to anchor everywhere as there are pipelines at the sea bottom in certain areas. In this study this is neglected.

Sail to port
If there is a significant malfunction or the conditions on the water, that requires the barge can no longer sail, the barge will sail to a port for shelter. It is considered that downtime due to reparations and maintenance can be done in the time that is not workable, so that is the time that the barge is in the port. The closest port is at IJmuiden.

2.4. Cost components

This section focuses on the cost components that are used to calculate weekly cost, cost per cubic meter and total project cost. These are all estimations based on multiple sources. The main sources are an TSHD cost indication written by van Rhee (2022), a general vessel cost indication for dredging vessels provided in CIRIA (2009) and the Blueconomy (2010) report for economics and effects for nourishing the dutch coast.

Indexation
All cost indications are time dependent and the values change, because of inflation and changing material cost. In this report the year 2022 is held as a benchmark for the cost calculations. That means that from all sources the source date has been set and an indexation has been made to extract the given cost to the year 2022. An overview of indexations is shown in Appendix B.

2.4.1. Traditional cost components

As a baseline the cost components are provided for a trailer suction hopper dredger. As the main lines of costs are equal for the different systems. Additions and changes to these cost will be stated explicitly.

Depreciation & interest
Like all assets, TSHDs are subject to depreciation and interest expenses over their useful life. Depreciation refers to the gradual decrease in the value of an asset over time due to wear and tear, obsolescence, and other factors. TSHDs are typically depreciated using a straight-line method, which means that the depreciation expense is the same each year over the useful life of the vessel. The useful life of a TSHD is determined by factors such as the vessel's design, construction quality, maintenance history, and operating conditions. In general, TSHDs have a useful life of around 20-25 years.

Interest expenses, on the other hand, refer to the cost of borrowing money to finance the purchase or construction of the TSHD. The interest rate is determined by a number of factors, including the borrower's creditworthiness, the lender's risk assessment, and prevailing market conditions. The interest expense is calculated based on the outstanding loan balance and the interest rate. An overview of TSHD depreciation and interest estimates is given in CIRIA (2009) and a recent indexation is given in CIRIA (2021).

Maintenance & repair
Maintenance and repair costs are also significant expenses associated with owning and operating a TSHD. These costs are necessary to ensure that the vessel remains in good working condition and meets regulatory requirements. Maintenance costs refer to the expenses incurred for routine inspections, cleaning, lubrication, and minor repairs. These expenses are essential for preventing equipment failure, minimizing downtime, and extending the useful life of the TSHD. Examples of routine maintenance tasks include changing the oil and filters, replacing worn hoses and belts, and cleaning the engine and hydraulic systems.

Repair costs, on the other hand, refer to the expenses incurred for fixing or replacing damaged or worn components of the TSHD. Repair costs can be significant and can vary depending on the type and extent of the damage, the availability of replacement parts, and the cost of labor. Examples of repair tasks include replacing a damaged suction head, repairing a cracked hull, or replacing a failed engine or hydraulic pump (Butler, 2012).

Insurance
Owned equipment needs to be insured in case of unexpected problems, such as malfunctions or collapse. The insurance premiums are expected to be the same for the barges and the crawler as the THSD. This means that the insurance is 0.03% of the total value of the vessel per week as suggested by van Rhee (2022).

Effective management of maintenance and repair costs is essential for ensuring the long-term profitability and reliability of a TSHD. This involves implementing a maintenance program that includes regular inspections, preventative maintenance tasks, and timely repairs. It also involves carefully managing repair costs by working with reputable suppliers, negotiating favorable pricing, and monitoring repair quality. Cost indications are also provided in CIRIA (2009).

Sounding vessel
A sounding vessel is a type of vessel that is used for conducting surveys of the seabed to gather information about water depths, bottom features, and the composition of sediment or rock. These vessels are often used in conjunction with dredging projects to help plan and execute dredging operations. Cost estimates for the sounding vessel are given in Blueconomy (2010).

Transport vessel
Renting a vessel to transport personnel to and from a dredging also adds weekly cost. The rental cost

of the vessel may vary depending on factors such as vessel size, equipment onboard, and the duration of the rental period. The crew wages and expenses may include salaries, food, and lodging, as well as any other expenses that may be incurred during the rental period. Fuel costs will depend on the distance between the ship and the shore, the fuel consumption rate of the vessel, and the current price of fuel. Estimates for all including cost of the transport vessel are given in Blueconomy (2010)

Mobilisation cost
Mobilisation costs are the expenses associated with transporting dredging equipment and personnel to a project site. These costs can have an impact on the overall project budget and timeline. Blueconomy (2010) provides mobilisation cost estimates for small TSHD of 3500 m^3, in this project the mobilisation cost for TSHD's is set as this (indexed) rate.

Execution cost
Execution costs for a dredging project typically include the costs of labor for crew and support personnel, port fees, refuelling, equipment rental fees, and other miscellaneous expenses. The specific costs will vary depending on the scope and duration of the project, the type of vessel being used, and the operating conditions.

Wear and tear
Wear and tear costs are the expenses associated with the gradual deterioration of the vessel's components due to usage and age, which requires repair or replacement of worn-out parts. In the case of a dredging vessel, the components that are most subject to wear and tear are the pipelines and dredging pump. The pipelines of a dredging vessel are subject to wear and tear due to the abrasive nature of the materials being transported, such as sand and rock. Over time, the pipelines may develop leaks, cracks, or other damage, which can result in reduced efficiency and increased maintenance and repair costs. Replacement of pipelines can be a significant expense for dredging vessel owners and operators.

The dredging pump is another component that is subject to wear and tear. The pump is responsible for extracting the material from the seabed and transporting it to the hopper or storage area on the vessel. The dredging pump is subject to wear due to the abrasive nature of the materials being transported, as well as the high pressure and velocity of the water flow. Over time, the pump may require replacement of parts such as impellers, shafts, and bearings, which can be expensive (van Rhee, 2022). For sand the wear and tear is summarized in a cost per cubic meter sand dredged of 0.25 €/m^3.

Personnel cost
The cost of crew for a trailer suction hopper dredger (TSHD) is dependent on various factors such as the number of working hours per week, the size of the vessel, and the location of the project. Local regulations may dictate the number and origin of the crew, which can impact the overall cost. For example, in Australia, Union regulations only permit local crew. The crew cost for a TSHD is the total sum of expat and local crew. To estimate crew costs, a table can be used that relates the costs to the length of the ship given in van Rhee (2022). The table distinguishes between expat crew costs and local crew costs.

For expat crew, the weekly cost varies depending on the length of the ship. The weekly cost for a TSHD less than 65 meters in length is €21,000, whereas for a ship greater than 135 meters in length, the weekly cost is €64,750. For ships between 65 and 135 meters in length, the weekly cost increases with the length of the ship. Local crew cost can be estimated using the following formula: Cost = 100*L - 3660 euros per week, where L represents the length of the ship in meters.

Fuel & lubrication cost
To estimate the fuel cost per week for a trailer suction hopper dredger (TSHD), the fuel consumption per week in tons must be multiplied by the unit price for fuel, which is typically expressed in US dollars per tonnes and can be found online. The fuel consumption rate can be determined using a specific consumption value for a chosen marine diesel fuel, such as IFO 380. In this research the fuel rates for the sailing of vessels is imported from the OpenTNSim model. However, for the dredging pump a general calculation method is used based on the power of the pump.

In this fuel cost estimation for the dredge pump the IFO 380 marine diesel fuel is used, the fuel consumption rate can be estimated using the following formula: consumption = 0.19 liters / (hour * kW) (van Rhee, 2022). This formula takes into account the specific density and energy content of IFO 380, as well as the power output of the TSHD's dredging engines in kilowatts. To determine the total fuel consumption per week, the fuel consumption rate should be multiplied by the number of hours that the TSHD uses its dredging pumps each week.

Lubricants are essential for ensuring the proper functioning of the TSHD's engines and other machinery. A general rule of thumb for estimating lubricant costs is to allocate approximately 10% of the total diesel cost as lubricant costs. In reality, this can vary depending on the type and condition of the TSHD's machinery, as well as other factors such as the frequency of maintenance and the quality of the lubricants used.

Overhead cost
When estimating the total cost of operating a trailer suction hopper dredger (TSHD), it is important to account for various overhead costs that may not be directly related to the vessel's day-to-day operations but are still necessary for the operation of the business as a whole. These overhead costs may include items such as office rent, salaries for administrative staff and other miscellaneous expenses. (Blueconomy, 2010) suggests 10% overhead cost.

2.4.2. Changing cost components for Slow Sailing

In comparison with the TSHD some system components' cost estimations will be different based on the system characteristics.

Cost of barges
Self propelled dumping barges that are used are also provided in CIRIA (2009). Different sized barges are given. Thereby, it is explicitly stated that in most cases the future vessel owner will have a large say in the specifics of the vessel. So, there is not such as one type of vessel. Vessels can be selected from different sea going classes. As stated before the interest lays in the barges that are seagoing, but have a restricted navigational area. They are selected as coastal dredging works are the main goal of these barges. In practice this often means that the barges will be allowed to sail 20 nautical miles offshore, which is sufficient for the project goal.

Depreciation & interest
The depreciation and interest cost indications are dependent on the utilisation period of the vessel. As companies own vessels they have to take into account that a barge will not be able to be occupied for a project all the time. The utilisation period can therefore be low, 20 weeks to take as example. In this project the barges will be used solely for the continuous sailing. Therefore the utilization weeks are higher and the weekly cost are lower. The utilization weeks will be set to be the workable weeks that the system is assumed to be working. In a case with a 90% workability rate the utilisation weeks is: 90% x 52 = 47 weeks. All regulatory and repair are assumed to be able to fit in the remaining 5 weeks.

Conversion barges
The barges will be designed to sail without onboard personnel. This means that the barges need extra equipment to be able to sail, navigate and be monitored. The viability has been researched by Sweco and it is provided that it costs €167.000 to convert a barge into a semi-autonomous barge. This will be added to the total value of the barge on which the depreciation and interest is dependent. The cost solely includes the cost for the conversion of the barge. Other cost coming with the system will be mentioned such as the cable connecting the crawler to its electricity source stand apart.

Maintenance & repair
The maintenance and repair cost in CIRIA (2009) are based on the number of service hours per week. As the maintenance and repair cost for restricted area barges are based on 84 service hours per week,

an additional factor needs to be included in which the actual number of service hours of 168 per week has been taken into account. CIRIA (2009) reports this factor to be 1.6.

Personnel cost

The personnel cost related to the barges are different than the personnel cost for the TSHD. In **?** Sweco found that the operational cost from the barges are 50 euros per sailing hour in 2022. It is in that economical perspective included that multiple barges can be overlooked by one person at a monitoring facility. It is even recommended to use more than one barge for the economical feasibility. As the 50 euros per sailing hour result in a yearly cost of €438.000, based on a full hours used in the system. It will be used to install 3-4 full time appointments to realize the system year round.

Although the initial idea of the Slow Sailing concept as described by Sweco was one full time person overlooking the fleet, it is confined that also management cost will need to be added. The management cost are there for project overlooking, evaluation of system progress etc. Management cost for the Slow Sailing system are set to a lower rate as the TSHD as the expected workload per week is lower due to slower and more straightforward and clear execution of the dredging works. The management cost are set at 8400 euros per week. This is also used as an input for the sensitivity to the total cost, which can be seen in Chapter 4.

Absence of cost components

Some of the cost components related to the TSHD are not included in the cost interpretations of the Slow Sailing system. First, there is no personnel vessel needed to bring personnel from and to the vessel as there is no personnel on board the vessel. Also, since the barges are used solely for the nourishment program of the dutch coast, there is no mobilization and demobilization needed as barges will always be nearby or already in use.

Thereby, the sounding vessel is still included in the cost and also is believed to be able to carry out another task. As the system is new, it can be plausible for some errors to occur. The sounding vessel is believed to sail out to a barge and carry out emergency tasks. What these tasks can be, is related to the actual implementation and software on the barges. This can be simplified to the sounding vessel sailing to the barge and resetting the software. Execution cost presented in the overview of the TSHDs are also used in the Slow Sailing system, as there might be a need for extra hands in these emergency operations, but also in replacing buoys, carrying the crawler out of the water in case of malfunctions etc.

2.4.3. Additional cost components Slow Sailing

As the Slow Sailing concept has different components compared to the TSHD it comes with several cost components that need to be added to get a complete overview.

Crawler

The so called ’subdredge’ costs an estimated $3.000.000 or roughly €2.800.000 based on a conversion rate of 0.93 euro/dollar. It has a lifetime of 7.5 years. The maintenance and repair of the crawler is set to 178.000 euros per year. The weekly cost of the crawler is directly dependent on the number of weeks the crawler is in use in a year and is thus directly related to the workability of the system. These cost estimates are provided in Sweco (2022b).

Energy crawler

The energy required to power electronic crawlers can come from a variety of sources, including electricity, batteries, or fuel. Electricity is a common source of energy for electronic crawlers that are used indoors or in areas with access to power outlets. The green electricity is assumed to be delivered at a cost price of 20 ct / kWh. In this price production and transport is included. This is an assumption and not further investigated. Price indications by Sweco (2022b) are used indicating that for the 0.2 €/m^3 the energy can be delivered at the crawler. This can be realized either by a connection to shore or to a nearby windmill or energy distribution center at sea. On the other hand, if delivery of green electricity is not possible, it can locally be produced with a generator incorporated in the coupling system or on the barges. Then it is expected that the CO2 emission will be the same as the suction energy system of the TSHD system.

Coupling system
In order to make the system run smoothly without any human interaction the barges the barges need to be filled by an automated system that connects the pipeline to the vessel. As this is not yet existent an estimate has to be made for this system component. In earlier research Sweco assumed €500.000 for this equipment. That is also assumed in this study.

Pipeline
The crawler needs to be connected to the coupling system and anchorage buoy. In Ciria also pipeline components and lifetime estimates are provided for pipelines. In this case 20 m pipeline with a diameter of 400 mm. 10 pieces are needed for the 200 meter pipeline. Service life and M+R for the pipeline are dependent on the type and quantity of the soil. This is reflected in the wear and tear cost in the case of the TSHD. For sand a price of 0.25 €/m^3 is assumed. This is normally covering the entire pump and pipeline system on a TSHD, but is now assumed to cover the cost and maintenance and repair for the long submerged pipeline. So the wear and tear cost equals the complete pipeline cost.

Emissions
In earlier cost overviews the cost for emission of greenhouse gasses was not included. With the growing importance of the emissions the dutch government and European law started pricing these emissions. In this study only the emission of CO2 is considered, although the actual emissions of diesel also include different gas types such as NOx. The Emissions Authority of the Netherlands (Emissieautoriteit) oversees the implementation of the Dutch carbon tax, known as the CO2-heffing. The carbon tax applies to companies that emit large amounts of carbon dioxide (CO2) and is intended to provide incentives for companies to reduce their emissions. The CO2-heffing applies to companies that emit more than 25,000 tonnes of CO2 per year. These companies are required to purchase emission allowances, known as CO2 allowances, to cover their emissions. The price of these allowances is set by the government and varies depending on the level of emissions and other factors.

The revenue generated from the CO2-heffing is used to fund renewable energy and other sustainability initiatives in the Netherlands. The goal of the carbon tax is to encourage companies to reduce their emissions by investing in cleaner technologies and adopting more sustainable practices.The cost of the CO2-heffing can be significant for companies that produce large amounts of emissions. However, the tax is designed to provide an economic incentive for companies to reduce their emissions, which can ultimately help to mitigate the impacts of climate change. In this study it is assumed that a company executing the dredging project of the dutch coast will be over the 25,000 tonnes of CO2 per year limit and therefore needs to pay the fees for every tonne CO2 in the system as given by NEA (2023) .

An additional CO2 system is also in place. The European Union Emissions Trading System (EU ETS) is a cap-and-trade system that covers carbon dioxide (CO2) emissions from certain sectors in the European Union, including power and heat generation, industry, and aviation (Dutch emission authority, 2015). Under the EU ETS, companies receive a certain number of emission allowances, which represent the right to emit a specific amount of CO2. These allowances can be bought and sold on the carbon market, creating a price for CO2 emissions. The relationship between the EU ETS and the CO2-heffing in the Netherlands is that the CO2 allowances purchased by companies under the CO2-heffing can also be used to comply with their obligations under the EU ETS. This means that companies subject to the CO2-heffing can purchase CO2 allowances on the EU ETS market to cover their emissions, and these allowances can also be used to comply with their obligations under the CO2-heffing, this results in a minimum CO2 price defined by the dutch government and an interchangeable market price at European level. If market prices drop below the CO2-heffing price an additional fee has to be payed. These minimum prices are used in this report. These prices are currently lower than the CO2 market prices, but are more stable and provide certain minimal prices for CO2. The market price is more volatile.

3
Feasibility exploration

The feasibility exploration chapter shows feasibility calculations in the given wind climate. It shows what model is used and which schematizations and interpretations are underlying to the results. This section provides results in terms of a proposed sailing speed and a related timing in the tidal cycle that will be used later in Chapter4.

3.1. Model choice & introduction

In order to compare different strategies a program is needed that can calculate energy consumption of barges and ships. In the search for a fitting model to be used in the research, multiple models were considered. These different models were assessed based on their accessibility, wind inclusion, route optimalization options, energy calculation possibilities and project tracking options. This resulted in Table 3.1.

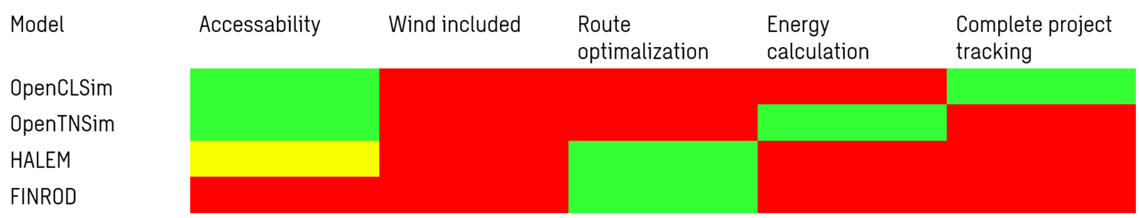


Table 3.1: Models characteristics overview

OpenCLSim
OpenCLSim is a model created by the cooperation of Delft university of technology, contractor van Oord and research institute Deltares. It is a Python package for complex logistics simulation. Dredging cycle logistics and tracking are included in the model. However, it does not include energy calculations that are needed in the project or any wind influence on the energy consumption. Also, there is no route optimalization in the model.

OpenTNSim
OpenTNSim is an open source Python package as well. It focuses on inland transport systems and is used to calculate energy demands of vessels that use the inland water transport system. In the model different positions, locations and vessels can be used to calculate distances, resistances and emissions (Jiang et al., 2022).

FINROD
FINROD is a model created by Svasek and combines flow information, topographical/environmental information and "timing" aspects to predict optimal navigation tracks, based on Lolla et al. (2012). It is an in-house software of Svasek and therefore only accessible on their local servers. It focuses on single

displacement every run and does not include project tracking.

HALEM
The HALEM model also focuses on route optimalization as can be seen in Halem (2019). It is created in order to optimize routes and can be incorporated in the OpenCLSim model to create a complete project tracker with a optimized route for the different runs.

Model choice
The OpenTNSim model is chosen as the model can be used directly to perform well based energy and emission calculations. The OpenTNSim version 1.1.2 is used in this research and a model description can be found on GitHub through TUDelft-CITG/OpenTNSim.

3.2. Workflow

The OpenTNSim program uses a workflow that calculates the energy consumption, fuel use and emissions for inland shipping vessels. It uses the ship dimensions, sailing speed through water and fairway characteristics to calculate resistances that the vessel experiences as well as energy demand and emissions for every step on a predefined path.

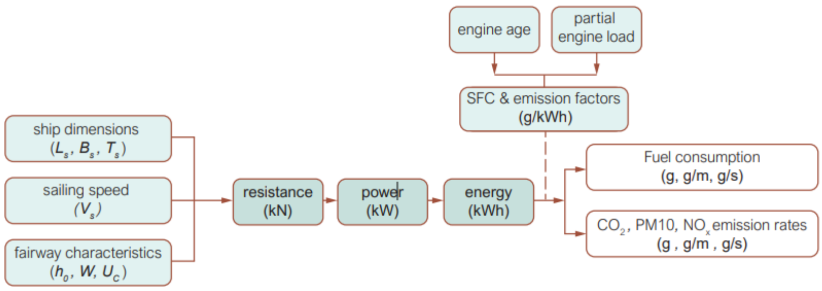


Figure 3.1: Methodology for estimating emissions for IWT vessels mage modified from Segers (2021) by TU Delft Ports and Waterways is licensed under CC BY-NC-SA 4.0).

3.3. Model theory

The program uses the method from Holtrop and Mennen (1982) to calculate the total resistance R_T. The total resistance is based on multiple resistance components, which added together lead to the total resistance as can be seen in Equation 3.1. A complete overview of the OpenTNSim model can be found in Appendix A.

$$R_T = R_f(1 + k1) + R_w + R_{app} + R_{res} \tag{3.1}$$

In which:
R_T = total resistance of the ship [kN]
R_f = frictional resistance [kN]
$1 + k1$ = form factor of the hull [-]
R_w = wave resistance [kN]
R_{app} = appendage resistance [kN]
R_{res} = residual resistance [kN]

In the next calculation step it uses different efficiency factors and the known velocity to calculate the effective horsepower (EHP), delivered horsepower (DHP) and brake horsepower (BHP). It can also include the power needed for hotel and living systems on board of a vessel if it there are any on board.

From the required power the energy can be calculated as the duration of the action is known. This energy (kWH) can be calculated as follows:

$$E = p * t \tag{3.2}$$

In which:
E = energy [kWh]
p = power [kW]
t = timestep [h]

The energy consumption is used to calculate the fuel use and emissions. In the program this is done by using empirical data of the specific fuel consumption (SFC) [g/kWh] based on the load and the type of engine, given some emission factors that specify the amount of emissions per unit energy consumed.

3.4. Added resistances OpenTNSim

In order to use the OpenTNSim model to its maximum capacities in this study it needs to be adjusted. As the program is focused on inland waterway transport and the nourishments in coastal environments are in open oceanic waters some additional factors should be taken into account.

In oceanic waters additional resistances appear that can modify the total resistance as described in Formula 3.1. Szelangiewicz and Żelazny (2018) give an Equation for the total resistance in real weather conditions.

$$R_T = R_V + R_C + R_A + R_W + R_R \tag{3.3}$$

In which:
R_V = ship resistance in calm water [kN]
R_C = additional resistance from surface currents [kN]
R_A = additional resistance from the wind [kN]
R_W = additional resistance from the waves [kN]
R_R = additional resistance of e.g. steering devices (e.g. rudder fin), that keep vessel on a given course (disturbance of the course are also caused by the impact of wind and wave).

These extra resistances are heavily dependent on local conditions and thus a choice must be made in which are added. In the complete system the cycle time will be linked to the tidal cycle time and therefore it is for now assumed that there is no extra resistance from surface currents. In this study the main focus is on the wind as the wind is expected to be the guiding factor to be influencing the barges. This is based on earlier research indications by Sweco. This changes the workflow from Figure 3.2 into the following Figure.

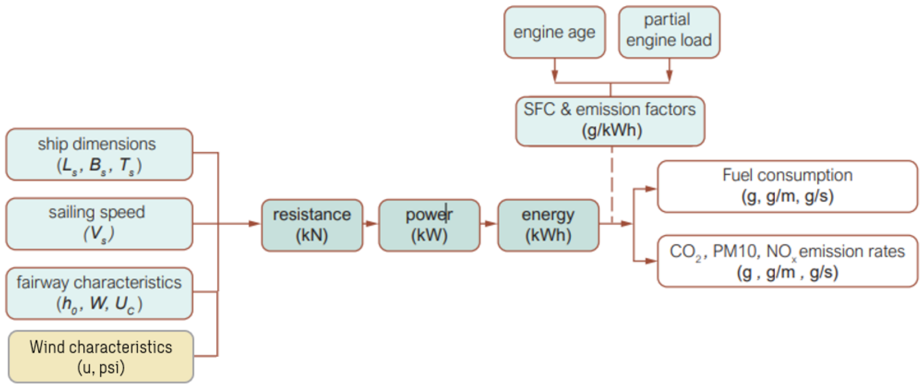


Figure 3.2: Edited calculation scheme OpenTNSim

3.4.1. Wind resistance

As the wind changes the total resistance it needs to be added as an input for the total energy consumption. Wind resistance is given in the ITTC recommended Procedures and Guidelines as an input for power trials and Equation 3.4 can be used to calculate the extra wind resistance as it calculates wind resistances (ITTC, 2021). In the calculations wind velocities are set constant for the duration of a sailing trip. As it is known that the wind direction and wind speed vary heavily over time this is a slight deviation from real conditions.

$$R_A = 0.5 * \rho_A * C_{DA}(\psi_{WRref}) * A_{XV} * V_{WRref}^2 - 0.5 * \rho_A * C_{DA}(0) * A_{XV} * V_G^2 \tag{3.4}$$

In which:
R_A = resistance increase due to relative wind [kN]
A_{XV} = area of maximum transverse section exposed to the wind [m2]
C_{DA} = wind resistance coefficient [-]
V_G = measured ship's speed over ground [m/s]
V_{WRref} = relative wind speed [m/s] at reference height, 0 means heading wind
ρ_A = mass density of air [kg/m^3]
ψ_{WRref} = relative wind direction at reference height; 0 means heading wind.

In order to incorporate this Equation into the OpenTNSim model some interpretations assumptions are made. These are the calculation of the exposed area A_{xv} and the related schematizing of the incoming wind angle.

Calculating A_{xv}
For the calculation of the wind resistance the area of the barges that is exposed to the wind is needed. In order to find the this area first the barge is schematized as a rectangular shaped vessel. The cross sectional view is given under the loaded and unloaded situation in Figure 3.3 Also the squared frontal and back view is shown.

To find the area A_{xv} for the schematized barge the wind angle is an important factor as can be seen in Equation 3.4. The barges are set to sail at slow speeds and so, it is assumed that the real wind angle on the barge is the same as the relative wind angle. Thus, there is no correction needed for the wind from the forward movement of the barge. Given that the wind angle is known for a given situation the incoming windangle α on the vessel can be used to calculate the area. The exposed area of the head of the barge B and the exposed area of the side of the barge L can be summed to provide the total area exposed.

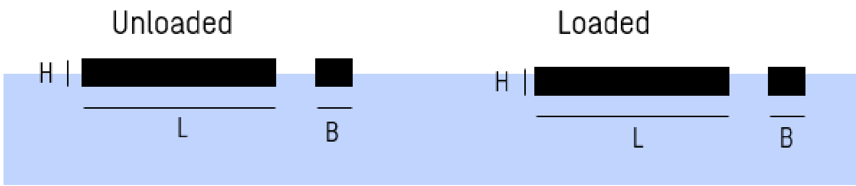


Figure 3.3: Barge schematization overview

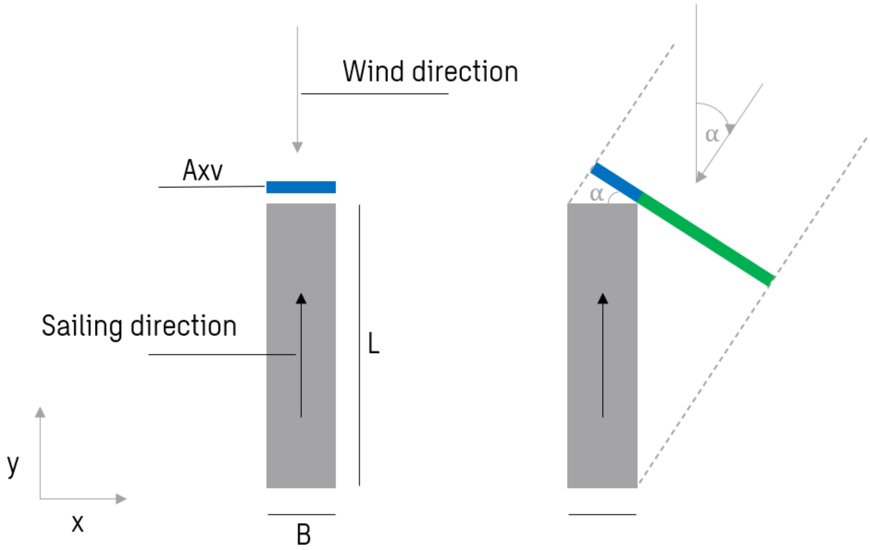


Figure 3.4: Schematized calculation A_{xv} under incoming wind angle

Calculating wind angle
The barges are simplified to have a rectangular shape. This means that the front and the back of the boat, or the stern and the bow in nautical terms, have the same shape and size. Therefore, all incoming wind directions can be schematized as angles coming in between 0 and 90 degrees to calculate the areas as can be seen in Figure 3.5. In the final calculation of the wind resistance, due to the Cd coefficient, the wind resistance from wind coming in under a wide angle helps the boat forward. Therefore, the extra resistance will be negative.

Example
To get an idea of the magnitude and influence of different factors in this Formula it is best to give an example. A barge sailing in open waters with wind coming in at an angle of 20 degrees with a wind speed of 7.9 m/s. The barge is sailing at a speed of 1 m/s and has a length of 60 m and a width of 11 m. The barge has an exposed height above water of 0.55 meter, thus sailing loaded. This results in an exposed area of 11.7 m^2 and the density of air is 1.225 kg/m^3. For the CD value for an incoming wind angle of 20 degrees the ITTC manual is utilized, in which for different vessel types the Cd value is given. In case the wind is coming in for an angle of more than 90 degrees this Cd value turns negative and therefore the total resistance decreases, for tankers (the most similar to the used barge) it is found that the Dd value is 0.79 (loaded).

$$R_A = 0.5 * 1.225 * 0.79 * 11.7 * 7.9^2 - 0.5 * 1.225 * 0.86 * 11.7 * 1^2 = 333.4N \quad (3.5)$$

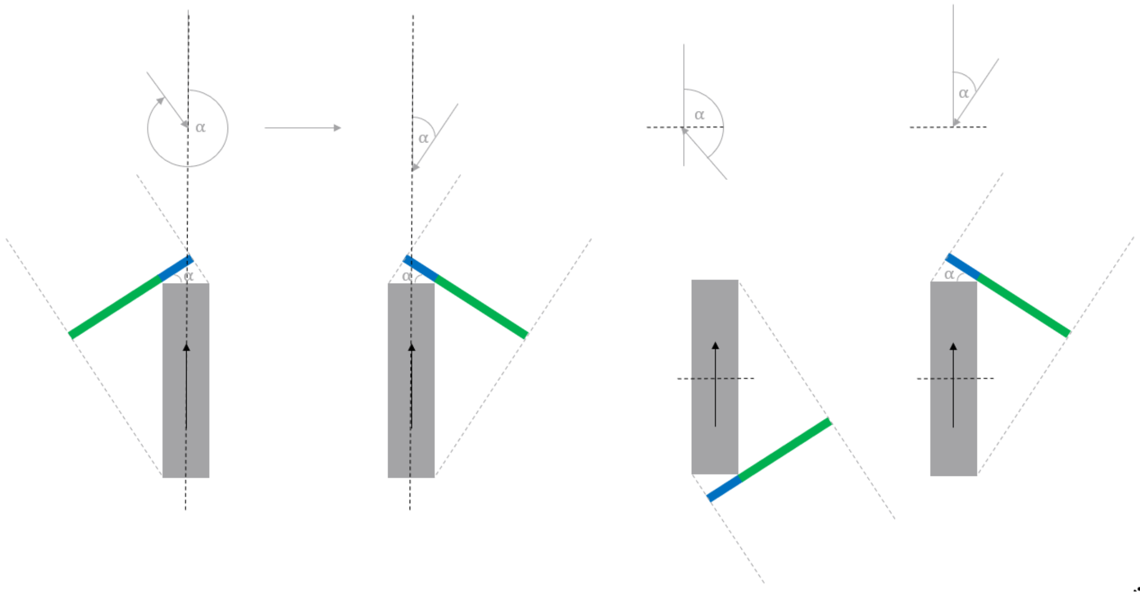


Figure 3.5: Correction wind angles for large wind angles

3.4.2. Rudder resistance

Besides direct resistance from the drag of the wind also causes another effect on the barge. As wind comes in under an angle under most circumstances the barge is also blown away from its course. The ship is pushed away from its course over ground and drifts away to the side. This is created by a moment from the wind coming from the side. This moment can be calculated by multiplying the wind force at the side of the barge multiplied by the length of the ship, which can be seen in Equation 3.6.

$$M_a = 0.5 * \rho_A * A_y * V_{RA}^2 * C_{Am}(\psi_{WRref}) * L \tag{3.6}$$

In which:
M_a = moment acting on the barge [Nm]
ρ_A = air density [kg/m^3]
V_{RA} = relative wind speed [m/s]
C_{Am} = aero-dynamical drag coefficient of the above-water part of the ship [-]
L = length of the ship [m]
A_y = area exposed in y-direction [m^2]

As the wind causes the barge to drift of its desired course the barge will have to create an equal moment in the opposite direction to counter the drifting effect. The barge can do this by the means of the rudder. As the rudder is put in an angle with the barge the horizontal force that is created by the rudder creates a moment around the centre of gravity of the barge. The compound effect of multiple components adding to this drifting can be seen in Figure 3.6.

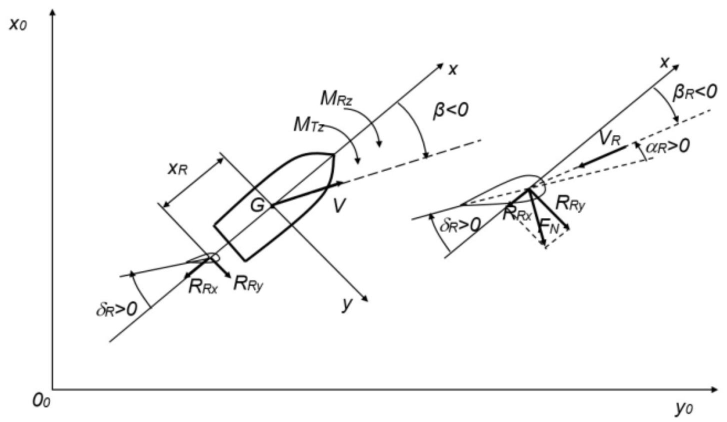


Figure 3.6: Momentum influence on barge and rudder angles

It can be seen that the force caused by the wind (M_{Rz} in this figure) causes the barge to rotate clockwise. As the rudder is placed under an angle at the end of the ship the water around it is deflected causing a rudder normal force F_N that acts perpendicular to the rudder. It should be noted that when multiple influences of on the drifting moments of the barge are considered the positive and negative directions need to be specified accordingly. This rudder normal force can be calculated with the following Formula:

$$F_N = 0.5 * \rho_w * \frac{6.13 * \lambda}{\lambda + 2.25} * A_R * V_R^2 * sin(\alpha_R) \tag{3.7}$$

In which:
F_N = rudder normal force [N]
λ = rudder aspect ratio (depth to width ratio of the rudder) [-]
A_R = area of the rudder $[m^2]$
V_R = water inflow velocity at the rudder [m/s]
α_R = effective rudder angle of attack [deg]

In this study the water inflow velocity at the rudder is assumed to be equal to the sailing velocity and the effective rudder angle of attack α_R is assumed to be the same as the rudder angle, δ_R as shown in Figure 3.6. Żelazny (2014) shows that this is good for general estimations and it shows different values of λ for different vessel types with $\lambda = 1.695$ for bulk carriers used. The rudder area is found to be the area of the immersed middle plane of the barge divided by 60 as found in Marine Engineering (2015).

The normal force that is caused by the angle of the rudder can be divided up in a rudder resistance in the direction of the ships movement R_{RX} and a component in the perpendicular direction R_{RY}.

$$R_{Rx} = |F_N * sin(\delta_R)| \qquad R_{Ry} = a_y * F_N * cos(\delta_R) \qquad M_{Rz} = a_z * F_N * cos(\delta_R) \qquad a_z = a_y * x_R \tag{3.8}$$

In which:
R_{Rx} = rudder resistance [N]
R_{Ry} = rudder lateral force [N]
M_{Rz} = moment created by rudder angle [Nm]
a_y = influence coefficient of the hull over R_{Ry} force on rudder [-]
a_z = influence coefficient of the hull over $M_R z$ on rudder, assumed to be 1 [-]
x_R = distance to centre of gravity [m], assumed to be $L/2$
δ_R = rudder angle [deg]

As can be seen from Formula 3.11 the rudder normal force F_N is depending on the speed of the barge.

The rudder angle δ_R also influences the moment created by the rudder as shown in Formula 3.12. However if the ship sails with a certain given speed only the rudder angle is variable. The larger the rudder angle, the larger moment is created, however the rudder cannot be deflected infinitely and thus the moment created by the rudder angle has a maximum. As shown by Meurs (1978) the rudder behind a vessel can increase to 60 degrees before the lateral forces will decay fast.

Example
To get a feeling for the impact of the wind to the drifting of the barge and compensation by the rudder angle an example is shown ongoing on the previous example for the wind resistance. The input of the moment created by the wind changes, the Cd value changes to a Cd value related to the transverse direction of the vessel and is set to a conservative value of 1. The area changes as well, the height and length of the boat are multiplied by the sinus of the incoming wind angle. In this case with a sharp incoming angle of 20 degrees that area is only 5.7 m^2.

$$M_a = 0.5 * 1.225 * 5.7 * 7.9^2 * 1 * 60 = 13143Nm \tag{3.9}$$

That moments need to be compensated by the moment M_{Rz} created by the rudder.The script looks for the smallest angle that the rudder can be placed so that $M_{Rz} > M_a$. The influence coefficient a_y is assumed to be equal to 1, so that M_{Rz} equals:

$$M_{Rz} = x_R * F_N * cos(\delta_R) \tag{3.10}$$

At the angle of only 3 degrees it is found that:

$$F_N = 0.5 * 1025 * \frac{6.13 * 1.7}{1.7 + 2.25} * 10 * 1^2 * sin(3) = 519N \tag{3.11}$$

$$R_{Rx} = |519{*}sin(3)| = 18.11N \qquad R_{Ry} = 1{*}519{*}cos(3) = 518N \qquad M_{Rz} = 30{*}519{*}cos(3) = 15562N \tag{3.12}$$

So the added resistance for the barge is in this case very low, only 18.11 N and the rudder angle is 3 degrees. It is assumed the rudder can only be in angles of integers so that it overcompensates a little so that $M_{Rz} > M_a$

3.5. Schematization input

As the barges are sailing back and forth along the coast a way must be found in which the barges are put in the model. In this schematization it is showed how the barges are put in the model to recreate a realistic way of portraying the situation. The barges are set to sail perpendicular to the shoreline. As the tidal velocity is assumed to be sinusoidal in the direction along the coast the barges can be set to sail in a straight line from the winning location to the disposal location. As the tidal velocity is only perpendicular to the direction of the barge the speed through the water is not actually influenced by the tidal velocity. However, the speed over ground is influenced by the tidal velocity as is the position in the alongshore direction at which the barge will reach the disposal location. In this way the exact disposal location of the barge is set to be dependent on the timing of the barges leaving the winning location in relation to the tidal period. In either case the direction that the barge sails is set to be a straight line perpendicular to the coast for a given distance and the tidal velocity is assumed not to be a factor in the velocity of the barge from the winning location to the disposal location. Dependent on the timing, speed and sailing distance of the barges they could end up at the same alongshore position as shown in Figure 3.7 or in a different alongshore position shown in Figure 3.8.

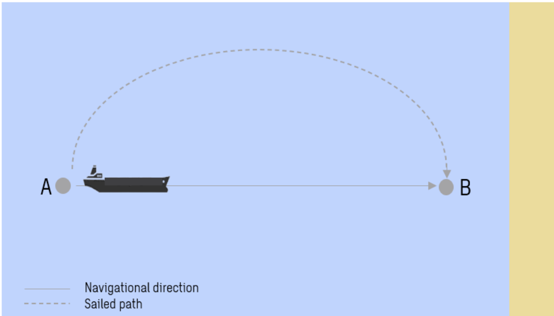


Figure 3.7: Sailing and displacement barge, symmetrical around tidal velocity

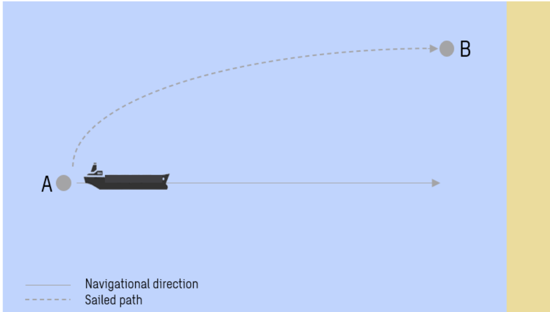


Figure 3.8: Sailing and displacement barge, not symmetrical around tidal velocity

The barge type and schematization is also an import factor in the resistant component calculations and the countering moment calculations. It is specified for only one barge size, for the calculation of the wind influence and knowledge gained is extrapolated to different sized vessels. The barge characteristics are: 60 m long, 11 m wide and 4 m height. The loaded freeboard height is 0.55 m and the unloaded freeboard height is 2.2 m. When the barge is unloaded it is filled with water. The underwater height is 3.45 m loaded and 1.7 m unloaded. Despite the barges being depicted as a rectangular shape the block factor used for the barges is set at 0.8. The limited freeboard height is provided by a reference barge shown in Chapter 2. The stability and maneuverability of the smaller barges in the Northsea wave climate has to be researched and is for now assumed to not be a problem.

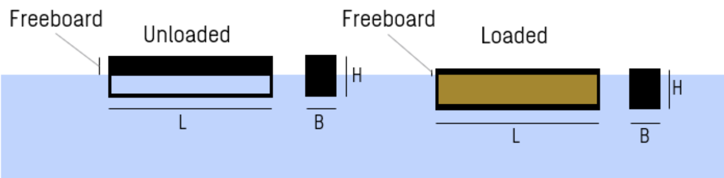


Figure 3.9: Loaded and unloaded situation of barge

3.5.1. Moment compensation

As the moment created by the rudder has a maximum based on the sailing speed it can provide an insight in the workable regions for the different sailing speeds with wind coming in under different angles. In the different Figures the angle and resistance are plotted for different sailing speeds and varying incoming wind angles. It can be read that for a certain incoming wind angle every line from the bottom is 1 Beaufort larger. The maximum of the rudder angle is set to 60 degrees so that when sixty degrees is reached the actual created moment by the wind cannot be compensated by the moment created by the rudder and the barge will drift of its course. Higher rudder angles will not lead to any more compensation, but only to increased resistance as the speed will decrease. The barges will sail loaded and unloaded both half of the total time. The exposed above water area of the unloaded barges is larger as can be seen in Figure 3.9. Unloaded conditions are therefore governing for this analysis and a full overview of loaded and unloaded conditions is shown in Appendix B.

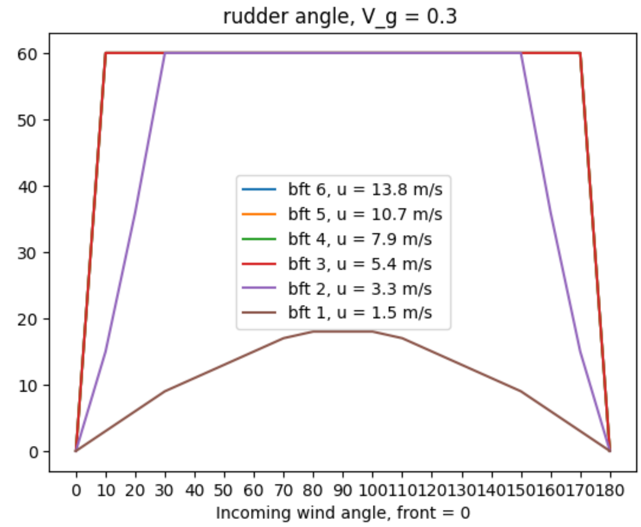


Figure 3.10: Rudder moment compensation angle, V = 0.3 m/s

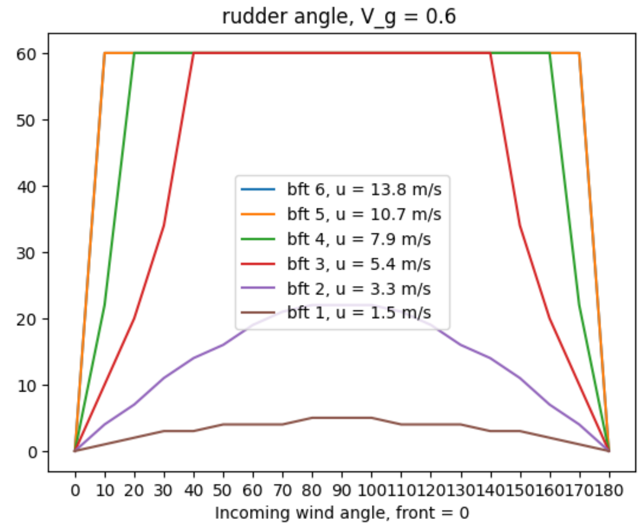


Figure 3.11: Rudder moment compensation angle, V = 0.6 m/s

For a speed of 0.3 m/s the barges can only sail in a straight line under all conditions at a Beaufort 1 as can be seen in Figure 3.10. This means that most of the time the barge will not be able to compensate the moment created by the wind and will drift off its course. As the sailing speed is very low the maximum moment that can be created by the rudder is low as well. At such a low speed only wind coming in under a very sharp angle can be compensated at Beaufort 2 and 3. As the incoming wind angle increases the area exposed to the wind increases and thus the moment created by the wind increases. That is why a higher wind speed need a larger rudder angle under the same wind speed. In Figure 3.11 the sailing speed is increased, leading to a larger maximum rudder angle. At a speed of 0.6 m/s the barges are able to sail under all angles up until Beaufort 2. Thereby Beaufort 3, 4 and 5 are showing some possibilities under sharp incoming angles.

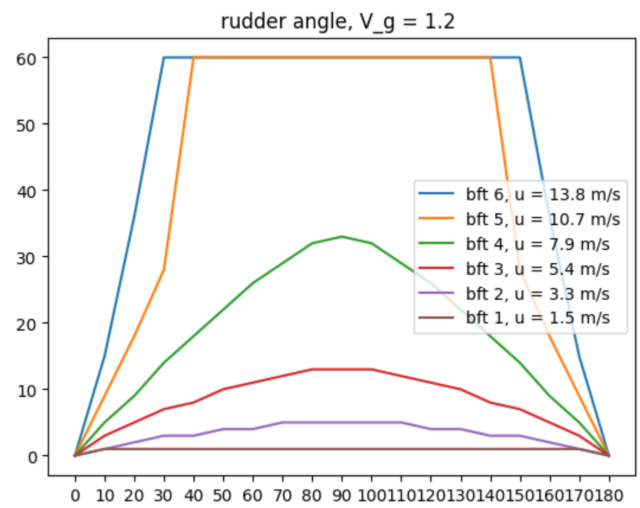


Figure 3.12: Rudder moment compensation angle, V = 1.2 m/s

Figure 3.12 shows the sailing workability limit in a sailing speed of 1.2 m/s. It shows the moment created by the wind can be countered for all incoming angles up until Beaufort 4. Under some of the sharper incoming wind angles the moment can also be compensated under the larger wind forces of Beaufort 5 and Beaufort 6. This speed is chosen as the minimal sailing speed for the barges. Under some angles the speed is actually vulnerable for drifting, which in highlighted in Table 3.2.

	BFT	Unworkable	Workable	% of time
Loaded	6	80-100	170-190, 350-10	0.15
Unloaded	5	40-140	130-230, 310-50	7.7
	6	15-165	105-255, 285-75	9

Table 3.2: Overview of situations the rudder cannot compensate enough

3.6. Timing in tidal cycle

The speed that was found in the previous section can be used to create a more clear picture of what a system with Slow Sailing barges could look like. A complete dredging cycle that the barges will go through will have 3 parts or phases. Therefore, the system proposed is implemented with 3 barges in which each barge is in a different phase of the cycle. One barge sails to the landfill site, one barge sails to the disposal site and one fills. The sailing distance is set at 13 kilometers making the sailing time both there and back at 3.1 hours. Filling with the electric crawler therefore also takes 3.1 hours to make the total cycle time 9.3 hours. Time needed for exchanging of the cycle parts is not taken into account.

3.6.1. Tidal current

As the barges sail towards the shore they are influenced by the tidal current. In the earlier section in the workability and drifting due to the incoming wind the speed through the water (V_s) was the main component. In this section we focus on the speed over ground (V_g). The focus is different as the wind analaysis was aimed at sailing in a straight line through the water to be able to stay on course. In this paragraph it shows that the actual path of the barge is not a straight line, but a parabolic shaped path based on the tidal current that is perpendicular to the sailing direction. A stationary barge that is not moving forward or backward is schematized in Figures 3.13 and 3.14. Figure 3.13 shows a barge at the beginning of a tidal cycle in a given position and as time progresses the barge will be drifted Northward as can be seen in Figure 3.14, which shows the barge after 3.1 hours. This is happening for the first 6.2 hours of the tidal cycle and after that the barge will be drifted the same amount Southward ending in the same longitudinal position compared to where it started.

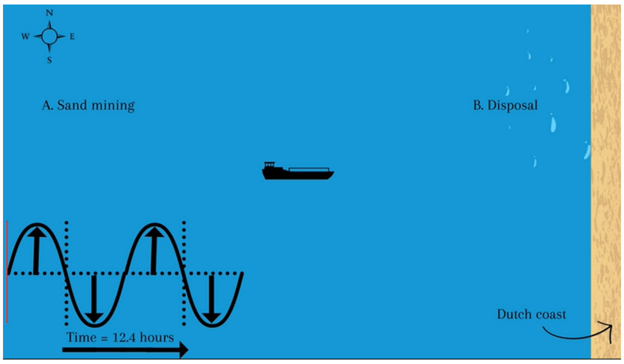


Figure 3.13: Stationary barge at start of tidal cycle

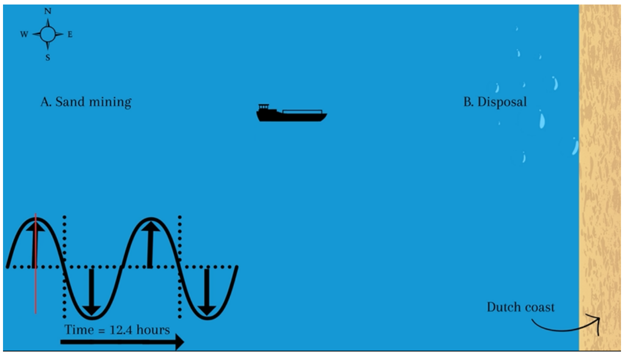


Figure 3.14: Stationary barge at one quarter of the tidal cycle

In the next situation the three barges are introduced that all are in a specific part of the cycle. One is filling at point A. One is sailing towards the shore, and one is sailing back to the winning point. During the three hours that these barges sail they are influenced by the tidal current. In order to end up at the same alongshore position as the barges started and vice versa, the same amount of time the barges should be drifted Northward as they are drifted Southward. As the barges sail for one quarter of the tidal cycle this means that 1.55 hours the barges need to be drifted Northward and 1.55 hours they need to be drifted Southward. If this is the case both the barge sailing towards the shore as the barge sailing back will end up in the same alongshore position as they started. This is visualized in Figure 3.15 where both barges start at point A in the tidal cycle. The are displaced Northward for the first 1.55 hours. Afterwards, in Figure 3.16 the barges drift downward again for the last 3.1 hours.

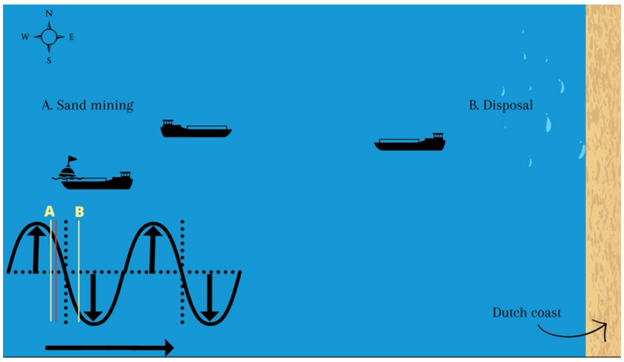


Figure 3.15: Three barges in system drifting Northward

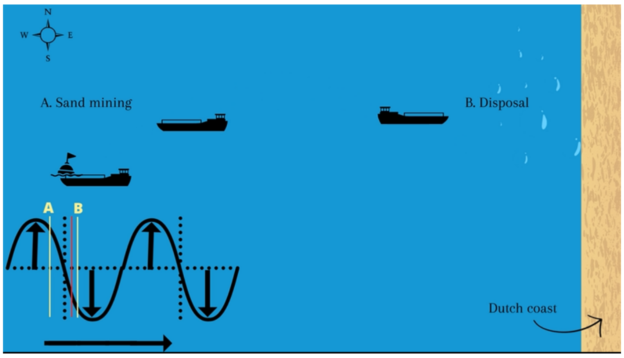


Figure 3.16: Three barges in system drifting Southward

After the 3.1 hours the barges end up at point B in the Tidal cycle (shown in yellow in Figures 3.15 and 3.16. As the barges switch roles the next 3.1 hours the barges only face downward drifting tidal current as can be seen in Figures 3.17 and 3.18. This means that the barges need to do something to not be drifted all the way Southward. For this reason the speed on this part of the tidal cycle is increased to 1.7 m/s. This speed is picked as it compensates for the average tidal velocity of 0.5 m/s tidal current as shown in Chapter 2. So it is simplified to the barges being displaced for the 3.1 hours with an average velocity of 0.5 m/s, therefore they need to sail the extra distance of the displacement resulting in a speed of 1.7 m/s. After this sequence the barges reach point C in the tidal cycle as can be seen in Figures 3.17 and 3.18. Starting from point C they will be reach a symmetry in the timing of the tidal cycle again, this time being drifted Southward first and then Northward. After that the barges will again sail 1.7 m/s to compensate for the Northward displacement. As these two situations occur one after the other the speeds can be set at 1.2 m/s for half of the time and 1.7 m/s for half of the time.

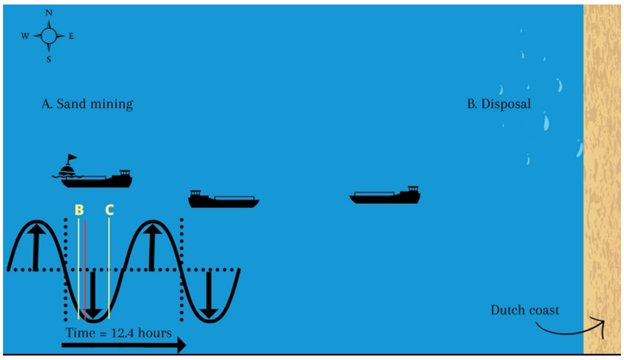


Figure 3.17: Barges moving Southward

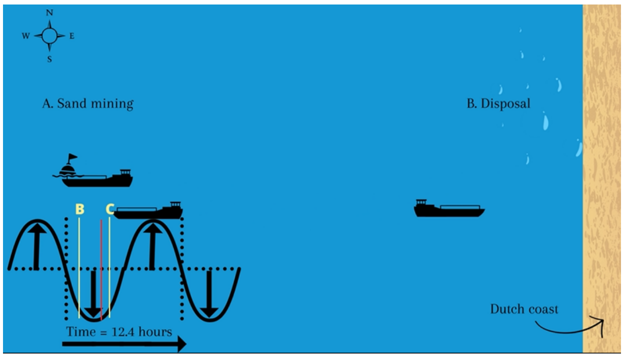


Figure 3.18: Barges increasing speed to cover compensation for tidal displacement

3.7. Sailing speed

The time percentages of conditions under which the barge with a sailing speed of 1.2 m/s cannot compensate enough in the given scenario are shown in Table 3.2. According to this Table 16.7% of the time the barges will have to sail faster in order to be able to compensate the moment. An additional 4% of the time the wind is above 6 Beaufort. Thus the total workability rate in this A-B scenario is rounded to 80% for the workable wind conditions. The sailing speed will be higher than 1.2 m/s for 50% of the time. As this is the case, it is expected that the workable regions are also increasing half of the time. For that reason the very ambitious workability rate of 90% is used further on. This is done because of the higher speeds half of the time and that in an implemented system the exact disposal location might also be a bit flexible, leading to a little margin in the angles the barges will sail. It must be noted that this is an optimistic choice.

The influence of the increase in speed in the energy use of the barges is still small. This can be seen in Figure 3.19 and Figure 3.20. The increase from 1.2 to 1.7 m/s is still very small in comparison with energy demands of regular speeds. In the loaded situation the increase is about 20 kWh, going from 40 to 60 kwh, which is low compared to the 400 kWh needed for a speed of 5 m/s. In the unloaded situation the increase is even smaller. The increase from 20 to 35 is also very small in comparison with the 275 kWh energy demand for sailing 5 m/s.

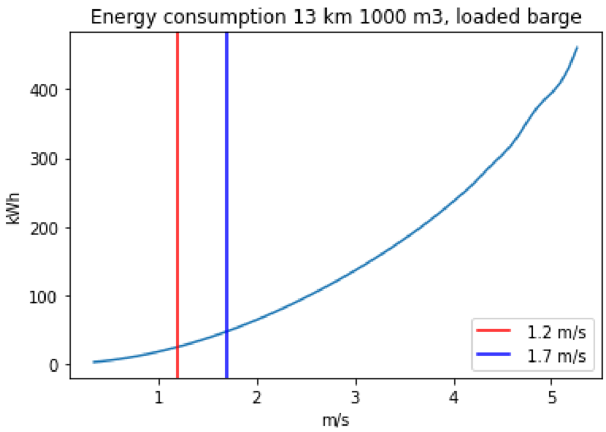


Figure 3.19: Energy consumption loaded barge 1000 m³

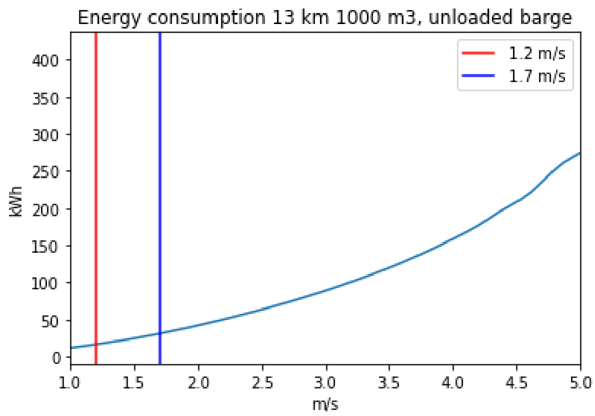


Figure 3.20: Energy consumption unloaded barge 1000 m³

3.8. Windfactor

In order to calculate the energy demand and emissions including wind influence faster for different vessel types a windfactor is calculated. Based on the known wind conditions it calculates the energy requirement based on the local wind conditions provided in Chapter 2. The windfactor calculation is shown in Appendix B and integrates the different leading wind directions and speeds with a loaded and unloaded barge to find the direct influence of wind on the barge. This windfactor is constant for all further used vessel types. A calculation scheme is shown in Figure 3.21. Appendix B shows that the windfactor for the barges is 1.27. This indicates that to calculate energy demands in this specific project area the general energy demand must be multiplied with the windfactor 1.27.

Figure 3.21: Calculation scheme windfactor

For a project in the dutch coastal waters a windfactor is found at 1.27, that needs to be used in order to calculate project wide energy demands. The different situations and different weather conditions are thereby summarized for a project and the general energy demands can be calculated by OpenTNSim.

3.9. Summary

This Chapter contains a lot of information that is used in the next Results Chapter. Therefore a small summary is convenient. The model that is used is OpenTNSim, an open source Python package that can calculate energy demands for vessels on a given path. The model is modified to include wind and rudder resistance components. These components are used to calculate the maximum moment that is pushing a barge off its course. In order to compensate this drifting the barge must steer, creating a compensating moment. This compensating moment has a maximum based on rudder angle and sailing speed. Therefore, it is used to calculate the sailing speed the barge must sail in order to sail under most circumstances. A speed is found of 1.2 m/s which, creates enough moment compensation. In order to fit in the tidal cycle, a barge must leave the winning point 1.55 hours before the change from ebb to flood. On its way back it endures current, which it needs to compensate by sailing a bit faster. The speed is than 1.7 m/s. This increase of speed does not have a huge impact on the energy demand of the barge. For the given project at Egmond aan Zee different wind conditions are considered that provide dominant wind speeds. This in order to calculate a windfactor that can be used to for project energy demands. The windfactor at this location is 1.27.

4

Results

The results Chapter consists of multiple sections that show energy, emission and cost calculations for different scenario's. After the scenario's result presentation the last section is a comparison of different scenario's and a sensitivity analysis. Both scenario's are pointed at a nearshore nourishment with a volume of 1.000.000 m^3 and a sailing distance of 13 km between winning and disposal location.

4.1. Scenario 1: Slow Sailing

The Slow Sailing scenario shows the energy use of different components and provides an overview that will be used to compare against the trailer suction hopper dredger (TSHD).

4.1.1. System

The Slow Sailing system uses three barges that cycle through three cycle phases in a total time of 9.3 hours. The first step is the filling of the barge with an electrical crawler in the sand-winning area in front of the Dutch coastal foundation. After that the barge sails to the nearshore of the Dutch coast and disposes its material and fills with water. When the barge has disposed its material it returns and sails back to the (stationary) winning point. Each step takes 3.1 hours and as the barges rotate all three barges are in a different cycle step at each moment. The crawler is seta at a fixed point, connected to a pipeline with a length of 200 m. It is expected that the crawler does not need to be relocated during operations. As the circle that the crawler is able to excavated by has a depth of 8 meters and a circle with diameter 400 m.

The timing of the barges sailing away from and towards the winning point is timed in relation to the tidal cycle. The barges sail away 1.55 hours before the tide switches and are drifted either North or South for this duration. After that they are drifted the opposite direction for the same duration and thus expected to end up and the same height as they started. The barges sail 1.2 m/s. As this symmetry use is not usable in the next 3.1 hours the barges will sail 1.7 m/s on their way back. If it is the way back or towards the shore does in this case not matter as they sail one time with 1.2 m/s, one time with 1.7 m/s and are filled as well during 3.1 hours. In this schematization the 1.7 m/s is used to cover an increased path and thus the barges still sail for 3.1 hours. A full explanation of the timing in relation to the tidal cycle can be seen in Appendix C.

4.1.2. Energy

The main goal of this report is to show the energy need of the system. In order to gain a good understanding of what is calculated and how, a calculation scheme is provided in Figure 4.8. The energy use for different barges is calculated in the OpenTNSim model. The input in the OpenTNSim model is separated into two parts. The first part calculates the loaded part of the barge sailing, the second part calculates the unloaded sailing of the barge. Together the loaded and unloaded paths combine into the energy use of a full dredging cycle.

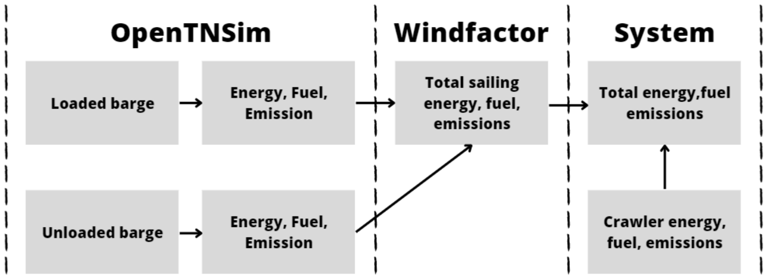


Figure 4.1: Calculation scheme energy use barges

The full cycle is used to calculate the total sailing energy, fuel and emissions. Based on local wind conditions a windfactor is calculated that is incorporated in the calculation of the total sailing contributions. Besides the sailing also the suction of the material is considered in the complete evaluation of the systems. The energy used to power the electrical crawler also contributes to the total energy use of the system. For the distance of 13 km from winning location to the disposal location in the nearshore of the Dutch coast the energy demands for the barges are shown in Figure 4.2 and Figure 4.3. As shown in Chapter 2 two velocities for the barges are calculated and used. As the barges sometimes have to compensate extra distance caused by off-timing from the tidal cycle half of all cycles. The loaded part of the cycle also is higher than the unloaded part of the cycle. The reason is that the wetted surface area is larger in this case resulting in higher viscous resistances. An increase in size as well as an increase in volume also leads to a higher energy use, the wave making resistance also increase in the case of higher speeds.

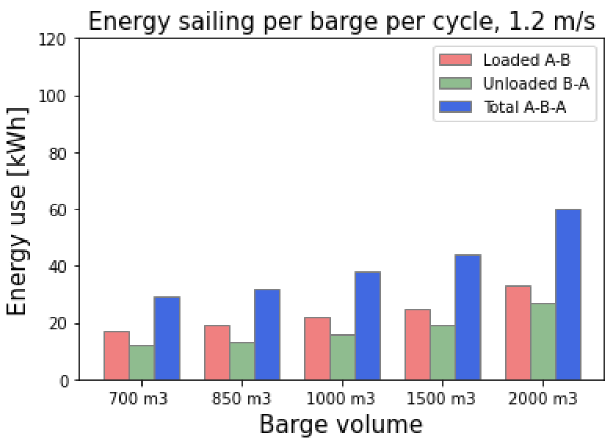


Figure 4.2: Cycle energy consumption barges 1.2 m/s

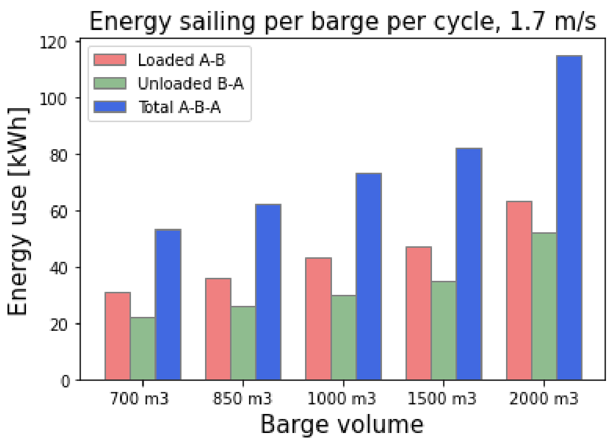


Figure 4.3: Cycle energy consumption barges 1.7 m/s

These speeds will both be used 50% of the time as shown in Chapter 2 and so the combined inputs of Figure 4.2 and Figure 4.3 can be used to show the average energy demand of the barges as shown below in Figure 4.4.

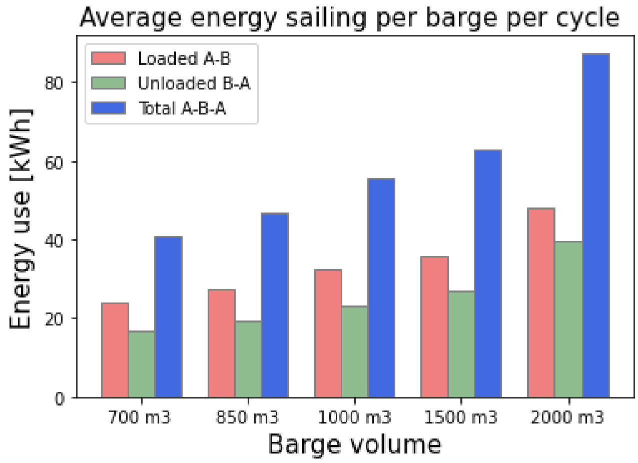


Figure 4.4: Cycle energy consumption barges average speed

Solar panels
An interesting exploring idea is to show the further expansion of green energy in the system by implementing solar panels on the roof of the barges. For example: the 1000 m^3 barges can use 75% of its area to be covered with solar panels. This means that approximately 500 m^2 is available for solar panels.Greenmatch (2023) shows that 25 m^2 can give provide up to 4 kW of power on sunny days. This results in 80 kW system that would cover most of the energy needed. A note on this is that weather should allow it and that some conditions some extra energy would be necessary. Further research into the solar panels is out of the scope of this project.

Crawler
The energy needed for the electric crawler is shown in Figure 4.5. It is based on a combination of the pipeline resistance over the total length of 200 meters and the energy that is needed to bring the mixture up to the desired height. On the system implementation of the 1500 m^3 barge a pipeline diameter is used of 0.4 m and for the 1000 m^3 barge a diameter of 0.35 m is used. An extended calculation is given calculation scheme provided by IHC that was modified for the project shown in Appendix C. The higher demand of sand in the same time frame requires the barge with 1500 m^3 to use more power.

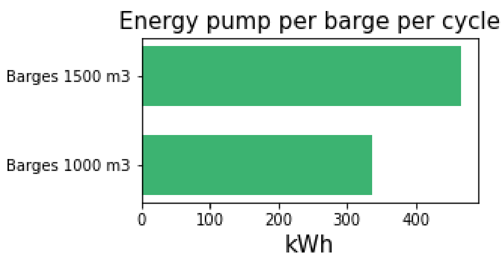


Figure 4.5: Energy demand crawler per barge per cycle

Barge size selection
As from this point on two barge sizes will be used for all Slow Sailing calculations. The goal of using two sizes for the barges is that it provides additional scaling related information compared to using only one barge size. It shows pros and cons for different size barges. Only two barge sizes are selected as they will be compared to the TSHDs. From the five barge volumes provided in Figure 4.2 the barges with a volume of 1000 m^3 and 1500 m^3 are selected. The 1000 m^3 barge is chosen as it is given as an entry point for this study and therefore a reference to earlier studies. The 1500 m^3 barge is chosen as it is seen as the biggest known barge size that is able to be filled with the capacities of the crawler. The 1580 m^3 TSHD is chosen as a more direct comparison to the 1500 m^3 barge and the 4280 m^3 TSHD is chosen as it is a more accurate description of what is actually used currently.

4.1.3. Emissions

The CO2 emission of the Slow Sailing system is reduced to the CO2 emission of the sailing of the barges. As the OpenTNSim model produces CO2 emission for sailed distances, these values can be used to later compare to the TSHD. It must be noted that these CO2 emissions are realistically calculated in OpenTNSim, but the scenario in which a diesel engine runs at very low power is undesirable. The electrical crawler is expected to get its electricity in a emission-free way and therefore does not contribute to the total CO2 emissions.

4.1.4. Cost

In this section, we provide an overview of the costs associated with the Slow Sailing barges and electrical crawler system proposed for the Dutch coast nourishment. We first present the weekly cost estimation for the equipment, including two sizes of barges (1000m^3 and 1500m^3) and the electrical crawler. Next, a production rate Table is presented for each barge size to estimate the amount of sand that can be transported and deposited in a given time. Finally, we combine the cost and production rate data to calculate the total cost per week for a nourishment project of 1,000,000m^3 at the Egmond aan Zee location.

A detailed cost breakdown for the weekly cost of Slow Sailing barges and the electric crawler can be found in Table 4.1. The weekly cost for the 1000 m^3 barge is estimated at €88,179, while the 1500 m^3 barge has a weekly cost of €112,563. The electric crawler has a significantly lower weekly cost of €13,982. These cost estimates provide valuable insight for evaluating the economic feasibility of implementing the Slow Sailing system for nourishing the Dutch coast.

Cost Barges			**Crawler**	
(Euro's per week)	**1000 m^3**	**1500m^3**		**700 kW**
Depreciation and interest	€ 7.645	€ 10.557		€ 9.343
Maintenance and repair	€ 14.880	€ 19.613		€ 3.799
Insurance	€ 1.268	€ 1.751		€ 840
Barge cost	€ 23.793	€ 31.921		
Number of barges	3	3		
Total vessel cost	€ 71.379	€ 95.763		
Operational crew	€ 8.400	€ 8.400		
Management crew	€ 8.400	€ 8.400		
Total cost per week	**€ 88.179**	**€ 112.563**		**€ 13.982**

Table 4.1: Slow Sailing components cost overview

For a 1,000,000 m^3 project with a sailing distance of 13 km one way, the Slow Sailing system produces approximately 43,897 m^3 per week for the 1000m^3 barge and 65,845 m^3 per week for the 1500m^3 barge, based on a workability rate of 90% or 0.9. This results in a project duration of approximately 22.8 weeks for the 1000m^3 barges and 15.2 weeks for the 1500m^3 barge. These estimates can be used to plan and budget for dredging projects using the Slow Sailing system. Table 4.2 containing the production rate estimates is shown below.

Pruduction estimates			**1000 m^3**	**1500 m^3**
Project size (m^3)		A	1.000.000	1.000.000
Sailing distance (km)		B	13	13
Dredging				
	Suction (hours)	C	3,1	3,1
Sailing				
	Total distance	D = B * 2	26	26
	Average sailing speed (kn)	E	2,3	2,3
	Sailing time (hours)	F	6,2	6,2
Dumping				
	Positioning	G	0	0
Total Cycle		H = C+F+G	9,3	9,3
Weekly production barge				
	Operational hours	I	168	168
	Workability rate	J	0,9	0,9
	Effective hours	K = I*J	151,2	151,2
	Cycles per week	L = K/H	16	16
	Volume (m^3)	M	1.000	1.500
	Load factor	N	0,9	0,9
	Weekly production (m^3)	O = L*M*N	14.632	21.948
Total production				
	Number of barges	Q	3	3
	Total weekly production	R = O*Q	43.897	65.845
	Production weeks	S	22,8	15,2
	Cycles	T = A/S	370	247
	Total sailing distance (km)	U = D*L*Q*S	28.889	19.259

Table 4.2: Production overview Slow Sailing

Based on the weekly cost estimates and production rates, a total cost estimate per week for the Slow Sailing barges can be calculated and shown in Table 4.3. This includes the vessel cost, system component cost, energy and emission cost, and overhead cost. The energy cost also includes the cost for the energy attachment of the crawler. For the 1000m^3 barge, the total cost estimate is 88.179 €/week, resulting in a cost of 3.71 €/m^3 for the project. For the 1500m^3 barge, the total cost estimate is 112.563 €/week, resulting in a cost of 3.00 €/m^3 for the project.

Cost Estimate (€'s per week)			**1000 m^3**	**1500 m^3**
Vessels				
	Barges	A	€ 88.179	€ 112.563
	Sounding vessel	B	€ 14.000	€ 14.000
	Execution cost	C	€ 15.275	€ 15.275
Vessel cost		D = SUM(A:C)	€ 117.454	€ 141.838
System components				
	Crawler	E	€ 13.982	€ 13.982
	Pipeline	F	€ 10.974	€ 16.461
	Coupling point	G	€ 1.668	€ 1.668
System component cost		H = SUM(E:G)	€ 26.624	€ 32.111
Energy and emissions		I	€ 3.968	€ 5.337
Complete system cost		J = D+H+I	€ 158.428	€ 195.215
Overhead cost		K = J*0.1	€ 15.843	€ 19.522
Cost including overheads		L = J+K	€ 174.271	€ 214.737
Weekly production		M	€ 43.897	€ 65.845
Total cost (ex ATV)		N = O*1mln	€ 3.970.014	€ 3.261.234
Total variable cost per m^3 (ex ATV)		O = L/M	**€ 3,71**	**€ 3,00**

* no profit or risk margins included

Table 4.3: Slow Sailing cost overview

To better visualize the cost breakdown for the Slow Sailing system using barges of 1000m^3 and 1500m^3, two pie charts are provided below. These charts show the percentage contribution of each cost component to the total cost estimate per week. It should be noted that while some costs, such as execution cost and personnel cost, remain constant regardless of barge size therefore showing a smaller percentage cost, other costs such as vessel rent and system component cost increase with the size of the barge. This can be seen in the larger percentage of vessel rent for the 1500m^3 barge as compared to the 1000m^3 barge.

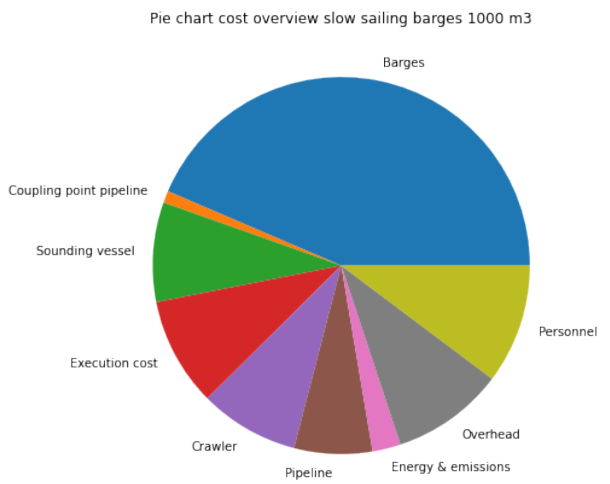


Figure 4.6: Pie chart Slow Sailing 1000 m^3 barges

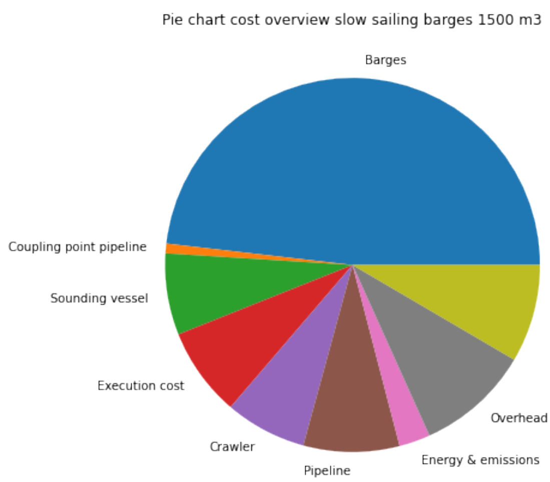


Figure 4.7: Pie chart Slow Sailing 1500 m^3 barges

4.2. Scenario 2: Trailer suction hopper dredger

The trailer suction hopper dredger (TSHD) scenario shows results that will be used to compare this scenario against the Slow Sailing system.

4.2.1. System

The TSHD system consists of one TSHD dredging the Dutch coastline. As in the scenario with the Slow Sailing system the distance to be covered from the winning location to the disposal stays constant and is 13 km. This means that the TSHD is modeled to sail 13 km from the winning location to the disposal location in the nearshore and sail back the same 13 km after unloading. The TSHD has a different exposed area under water and above water for the sailing from the shore and back as it sails loaded one way and unloaded the other way.

In the TSHD scenario there is no adaptation to the tidal cycle and the TSHD is expected to sail up and down with no waiting time between the cycles and to be in use for 90% of the time, which is equal to the Slow Sailing system. In the calculation the windfactor is included as well, but the extra movement or resistance due to the current or waves is ignored. As larger TSHDs are prone to sail faster the speed for the larger TSHDs increases. Thus the complete cycle time decreases as well for the larger TSHDs. The suction time for the TSHDs is for all sizes 90 minutes. This means that it is assumed that the TSHD's dredge pump capacity increase is proportional to the volume increase. Reference vessels and inputs for the TSHDs can be seen in Appendix A. The speeds for different volumetric sizes that are used are shown in Table 4.4.

TSHD volume [m^3]	900	1125	1580	2500	4280
Speed [kn]	10	10	11	11	12

Table 4.4: Sailing speed TSHD

4.2.2. Energy

In order to calculate the energy and emissions for the TSHD, a similar calculation scheme is used as in the Slow Sailing system. This means that also a windfactor is used to calculate the total project energy demands. Instead of the energy for the crawler an additional factor and demand of energy and emissions is added for the dredge pumps. Figure 4.9 shows the energy demand for one cycle of a TSHD sailing. The total energy use for the project will be shown in a later section.

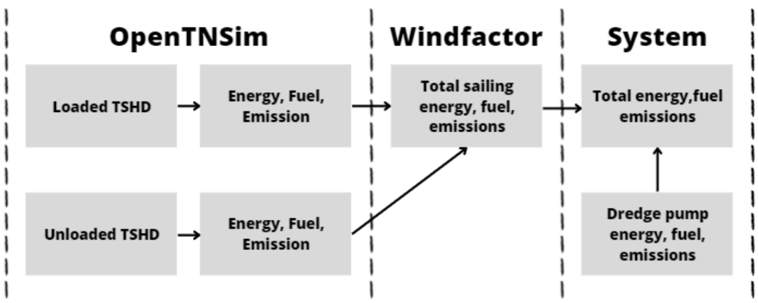


Figure 4.8: Calculation scheme energy use TSHD

The energy demand of different sizes TSHDs is shown in Figure 4.9. For the increased sizes it shows an increased energy demand per cycle as expected. The reason for this is that the larger vessels have a larger wet area that adds resistance and the larger vessels have a higher sailing speed. It shows the energy demand for a complete cycle as a loaded and an unloaded energy demand are presented. The the total energy demand of one full cycle is presented in blue.

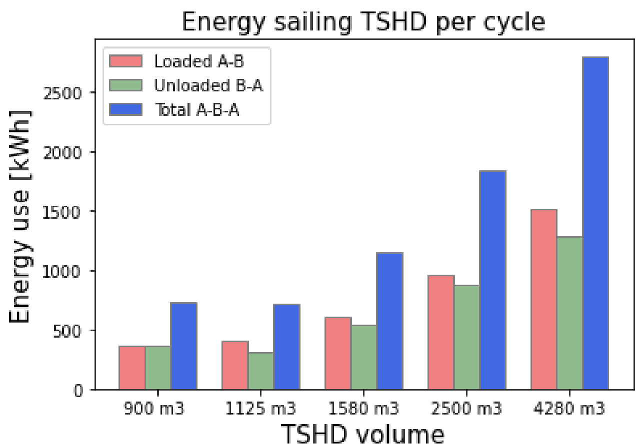


Figure 4.9: Cycle energy consumption TSHD

Dredging energy TSHD

The energy that is used for the dredging activities is based on the onboard pump. It is assumed that the pump power of the TSHD is used at full power since it is beneficial to fill the hopper within limited time. As the pump power increases with a larger volume the time to fill the the TSHD is set at 90 minutes.

$$E_{pump} = Power * 1.5 \tag{4.1}$$

TSHD size selection

As shown in the Slow Sailing scenario two TSHDs are chosen for further comparison. These are the 1580 m^3 and the 4280 m^3 TSHDs as they are respectively most comparable in size to the larger barge size and a close approximation of the currently used equipment.

4.2.3. Emissions

The CO2 emission of the TSHD is made up out of two parts. First the sailing emissions are calculated with the OpenTNSim model. This model provides grams of CO2 emitted by a TSHD sailing for a certain distance. These values are used for the emission of the TSHD during sailing. The other emission component comes from the dredge pump. In this case the diesel demand of the dredge pump in kg is converted to a kg of co2 emitted as in Blueconomy (2010). The conversion value used is 3.18 kg CO2 per kg Diesel.

4.2.4. Cost

The cost estimation for the TSHDs is presented in a similar format as for the Slow Sailing barges. First, the weekly vessel rent is provided, followed by the production estimates for the dredging operations. Finally, a total cost overview is presented, including the vessel cost, system component cost, energy and emission cost, and overhead cost. The following sections provide more details on each of these cost components.

Firstly, the weekly cost estimates for TSHDs are presented, focusing on the breakdown of the vessel rent cost for each size of equipment. This is a significant contributor to the total cost and comparing the vessel rent cost for different sizes of TSHDs provides insight into potential cost savings.

Cost Trailer suction hopper dredger (Euro's per week)	**1580 m³**	**4580 m³**
Depreciation and interest	€ 63.484	€ 146.529
Maintenance and repair	€ 47.004	€ 107.879
Insurance	€ 6.522	€ 15.054
Wear & tear	€ 17.763	€ 49.856
Local crew	€ 7.540	€ 8.740
Management crew	€ 24.500	€ 28.000
Total cost per week	**€ 166.813**	**€ 356.058**

Table 4.5: Cost component overview TSHD

The production estimates table for TSHDs provides an estimate of the weekly production rate based on a 90% workability rate. For the 1580m^3 TSHD, the production estimate is 70.959 m^3 per week, while for the 4280m^3 TSHD, it is 199.460 m^3 per week.

Production estimates			**1580 m³**	**4280 m³**
Project size (m³)		A	1.000.000	1.000.000
Sailing distance (km)		B	13	13
Dredging	Suction (hours)	C	1,5	1,5
Sailing	Total distance	D = B * 2	26	26
	Average sailing speed (kn)	E	11	12
	Sailing time (hours)	F	1,28	1,17
Dumping	Positioning	G	0,25	0,25
Total Cycle		H = C+F+G	3,03	2,92
Weekly production	Operational hours	I	168	168
	Workability rate	J	0,9	0,9
	Effective hours	K = I*J	151,2	151,2
	Cycles per week	L = K/H	50	52
	Volume (m³)	M	1.580	4.280
	Load factor	N	0,9	0,9
	Weekly production (m³)	O = L*M*N	70.959	199.460
	Production weeks	P =A/O	14,1	5,0
	Total sailing distance (km)	Q = D*L*P	18.284	6.750

Table 4.6: Production overview TSHD

The total cost per cubic meter estimate includes the vessel cost, system component cost, energy and emission cost, and overhead cost. The overview indicates that the total cost per cubic meter of material dredged for the 1580m^3 TSHD is 3.47 €/m^3. On the other hand, the total cost per cubic meter of material dredged for the 4280m^3 TSHD is 2.55 €/m^3.

Cost Estimate (euro's per week)			**1580 m³**	**4280 m³**
Vessels				
	TSHD	A	€ 166.813	€ 356.058
	Personnel vessel	B	€ 4.700	€ 4.700
	Sounding vessel	C	€ 14.000	€ 14.000
	Execution cost	D	€ 15.275	€ 15.275
Fuel and emissions		E	€ 14.511	€ 48.078
Total cost		F = SUM(A:E)	€ 215.299	€ 438.111
Overhead cost		G = F*0.1	€ 21.530	€ 43.811
Cost including overheads		H = F+G	€ 236.829	€ 481.922
Weekly production		I	€ 70.959	€ 199.460
Total variable cost per m³ (ex ATV)		J = H/I	**€ 3,34**	**€ 2,42**
Mobilisation cost		K	€ 135.125	€ 135.125
	Project size	L	€ 1.000.000	€ 1.000.000
	Cost per m³	M = K/L	€ 0,14	€ 0,14
Total cost (ex ATV)		N = L * (J+M)	€ 3.472.661	€ 2.551.262
Total cost per m³ (ex ATV)		**O = N/L**	**€ 3,47**	**€ 2,55**

* no profit or risk margins included

Table 4.7: TSHD cost overview

4.3. Comparison of systems

In order to determine the most cost-effective and environmentally friendly option for a dredging project, a comparison between the Slow Sailing and TSHD systems is necessary. The comparison includes evaluating the total energy consumption, CO2 emissions, total cost, and project duration of each system. By examining these factors, a clear understanding of the advantages and disadvantages of each system can be obtained. To compare the Slow Sailing system and the TSHDs, first their performance on energy use for a sailing distance of 13 km is evaluated. In this comparison, the axis of the relevant parameters are equal, allowing for a clear visualization of the differences between the two systems.

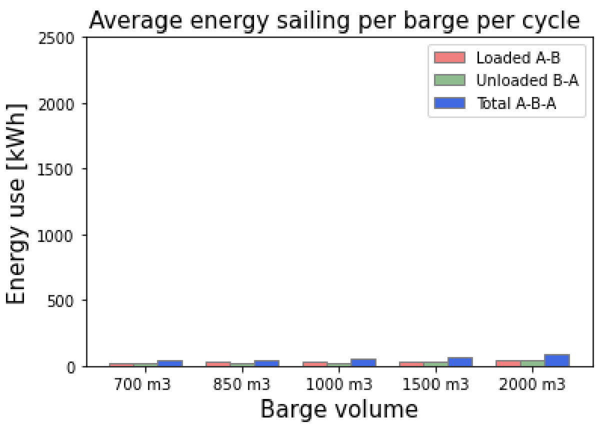


Figure 4.10: Energy consumption barges sailing scaled to TSHD

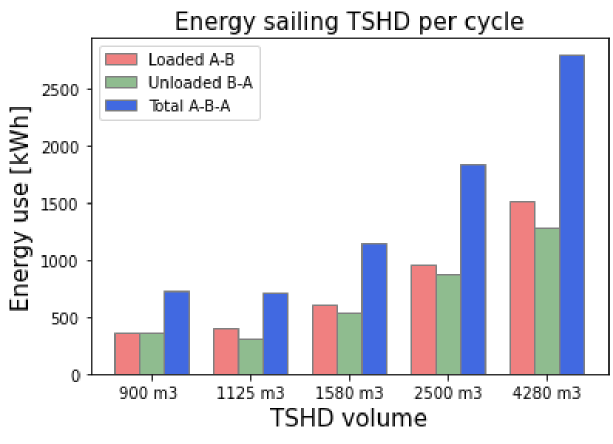


Figure 4.11: Energy consumption TSHD sailing

To compare the total energy demand for a complete project between the Slow Sailing system and the TSHD, a projection is made using a wind factor. This allows us to calculate the energy use for the entire project, which includes multiple cycles for both systems. By comparing the total energy use, an insight is gained into which system is more energy-efficient for dredging large volumes of material. The Slow Sailing system energy use is made up of the energy for the electrical crawler and the sailing energy. The energy demand of the TSHDs is based on the sailing energy as well as the dredging pumps. These factors and the total energy use can be seen in Figure 4.12. Thereby, also the aspect of time on these projects is depicted by showing the project duration for the different options in Figure 4.13. It can be seen that the total energy demands are referenced by mWh in the y-axis. The total energy of the barges is significantly larger for the crawler than the sailing. For the TSHD the sailing component is larger for the smaller TSHD, but smaller for the larger TSHD. It must be noted that the lower energy for the crawler compared to the dredge pumps on board the TSHD is remarkable. The different calculation methods lead to different outcomes. The same total amount of material dredged is expected to require less energy for the shorter pipelines of the on board dredge pumps of the TSHD compared to the crawler if both systems operate with approximately the same efficiency. Figure 4.12 shows an opposite outcome.

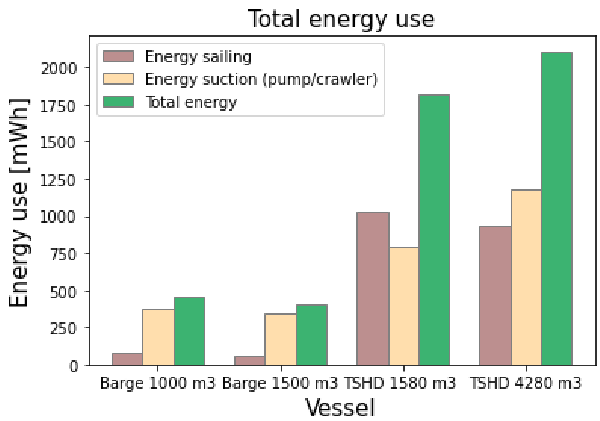


Figure 4.12: Project total energy consumption

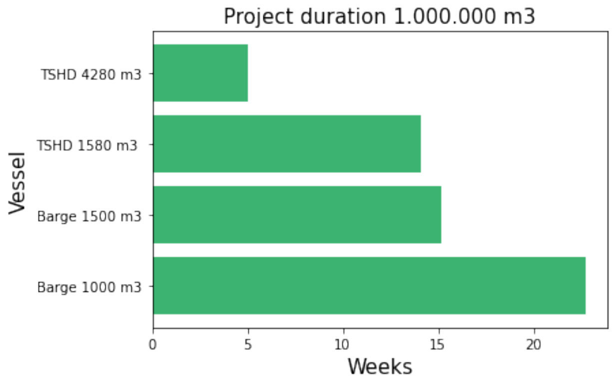


Figure 4.13: Project duration for 1.000.000 m³ project

3Figure 4.14 shows the comparison of CO2 emissions between the Slow Sailing system and the TSHD. The CO2 emissions for the Slow Sailing system are based on diesel engines and calculated by the OpenTNSim model. The pumping CO2 for the TSHD is based on Blueconomy estimates, while the electrical crawler is assumed to produce zero emissions. On the other hand, if delivery of green electricity is not possible, it can locally be produced with a generator incorporated in the coupling system or on the barges. Then it is expected that the CO2 emission will be the same as the suction energy the TSHD system. Figure 4.14 provides insight into the potential environmental impact of each system. It can be seen that the total CO2 emission for the TSHD system is in the order of 1000 tonnes CO2 larger than the Slow Sailing system.

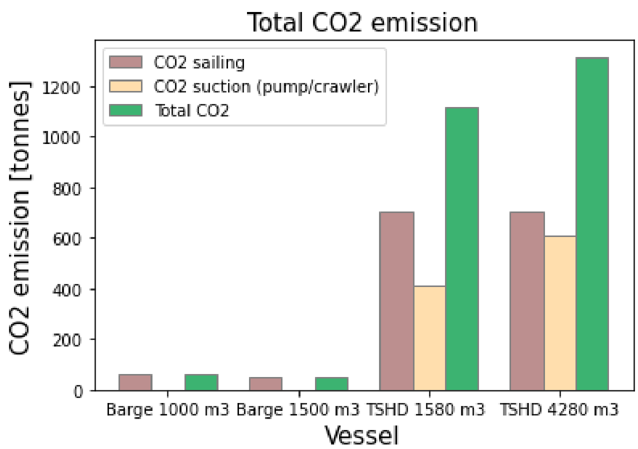


Figure 4.14: Project total CO2 emissions

Figure 4.15 in this comparison section provides a comprehensive overview of the key outcomes of the analysis. It presents multiple aspects of the two systems, reduced to numbers per cubic meter of sand dredged. The Figure shows the €/m^3, which indicates a preference for the 4280 m^3 TSHD with a difference of 0.45 €/m^3 compared to the 1500 m^3 barge. Additionally, the kWh/m^3 is most favorable for the Slow Sailing concept, while the kg CO2/m^3 is also in favor of the Slow Sailing concept. By presenting these metrics together, the Figure provides a clear comparison of the cost-effectiveness and environmental impact of each system.

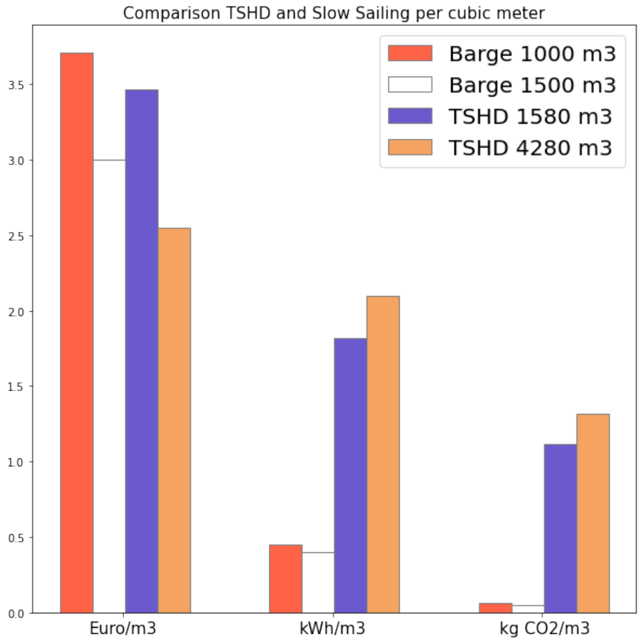


Figure 4.15: Comparison for barges and TSHD's of cost, energy and emissions per cubic meter

4.4. Risk analysis

As the system that is proposed includes some new equipment and techniques some of the risks can already be identified. The added value of mentioning these risks is that some possible mitigation methods can be identified upfront. This can lead to specific recommendations. In addition, the relative influence of some of the risks can be identified and will be shown in the sensitivity analysis in Section 4.5.

	R/O	Description	Chance	Impact	Risk level	Mitigation
1	R	Crawler system not able to stay out at all times	Medium	Medium	Medium	Execute wave impact study for pipeline and crawler
2	R	Electronic system shut down	Medium	High	Medium	Back-up vessel that is ready to interfere and reset barge. Automatic anchoring system in case of errors.
3	R	Higher sailing speed needed because of waves	High	Medium	High	Change sailing speed and adjust system
4	R	The coupling point is more expensive than expected	Medium	Low	Medium	Contact companies for development cost
5	R	Bad weather conditions during execution	Medium	High	Medium	Research weather changes and look at cost impacts for lower workability rates
6	R	The management cost are higher than expected	Medium	Medium	Medium	Research changes and look at cost impacts for higher management cost
7	O	CO2 price increases	High	Low	Low	Look at future rates and compare CO2/tonnes break even price with current project
8	O	Increased energy prices	Medium	Medium	Medium	Research influence on total cost
9	O	Lower barge cost, because no hotel functionality is needed	High	Medium	Medium	Research cost components for hotel elements in shipping

4.5. Sensitivity analysis

In addition to the comparison between the Slow Sailing system and TSHD, it is important to investigate the sensitivities of the system to different components and parameters. Uncertainties in costs or performance can have a significant impact on the cost-effectiveness of each system. Therefore, in this section, the sensitivity of the systems to changes in various components is analyzed, such as the cost of energy, CO2 emissiosn cost and the cost of management personnel.

CO2

The first sensitivity considered is the cost of CO2 per tonne. As discussed in an earlier chapter 2, minimal €/tonne CO2 prices set by the Dutch government have been used, which are actually lower than the current market prices. Two Figures are presented that focus on the upcoming cost increase in CO2 prices. The first Figure 4.16 shows the cost per cubic meter of material dredged for Slow Sailing barges and TSHDs, with varying CO2 prices until the year 2030. The second Figure 4.17 shows the long-term break-even cost of the two systems, assuming that CO2 prices continue to increase over time. The TSHD system is found to be more sensitive to CO2 price increases, with a much larger increase in cost for higher €/tonne CO2 prices. This shows that eventually, when the price per tonne of CO2 is increasing the cost breaks even at around 400 €/ tonne CO2.

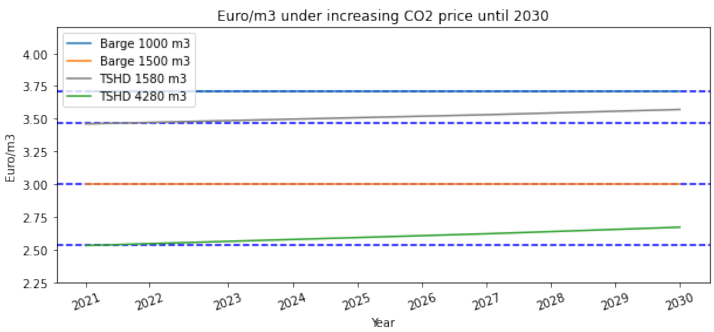


Figure 4.16: Cost increases TSHDs and barges under known CO2 price increase

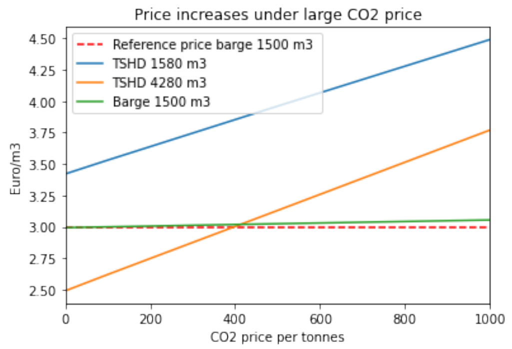


Figure 4.17: Break even price TSHDs and barges under increasing CO2 price

Workability rate

This section focuses on the sensitivity analysis of the system to deviations in the workability rate. Specifically, it is found investigate the impact of reducing the workability rate from the currently used value of 90% to 70%. Since the depreciation and interest of the crawler and barge are based on the workability rate, reducing this rate results in an increase in cost and a decrease in the estimated yearly production. For the 1000 m^3 barge, it is found that in the case of 70% workability rate, the cost increases to 4.93 €/m^3, while the yearly production decreases from 2.05 to 1.24 million m^3 per year. On the other hand, for the 1500 m^3 barge, it is found that the cost decreases from 3.00 to 3.75 €/m^3, and the yearly production decreases from 3.08 to 1.86 million m^3 per year.These findings suggest that the larger barge is more robust to changes in workability rate, with a lower increase in cost and a higher decrease in production compared to the smaller barge. However, reducing the workability rate still has a significant impact on the overall project cost and production, indicating the importance of maintaining a high workability rate.

Cost components

This section analyzes the sensitivity of the system to deviations in the estimated values of certain cost components. Specifically, we consider the management cost, the coupling point cost that connects the semi-autonomous barge to the pipeline, and the electricity cost used for the crawler. By varying these costs, we can assess the impact on the overall project cost. Starting with the management cost. As shown in Chapter 2 the management cost estimate is lowered for the Slow Sailing concept compared to the TSHD. The idea is that the long and steady process needs less management cost per week. So the total management cost might be the same, as the project duration is longer the management cost per week are lowered. It is assumed that the management cost are lowered to €8400 per week. The change

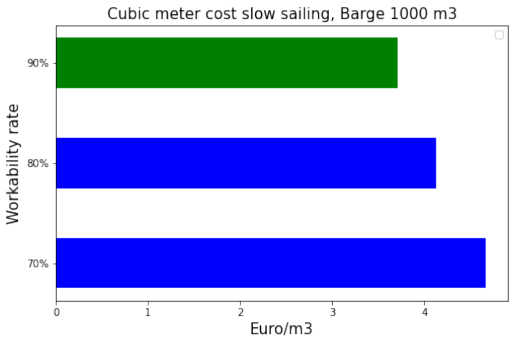


Figure 4.18: Workability influence 1000 m³ barges: €/m³

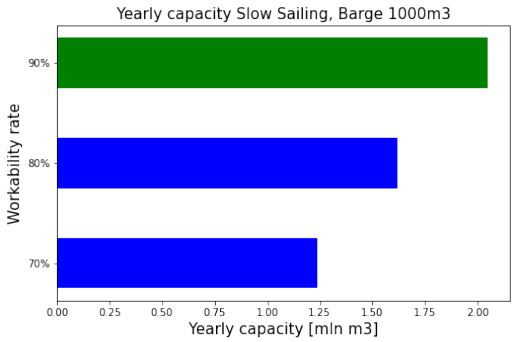


Figure 4.19: Workability influence 1000 m³ barges: yearly production

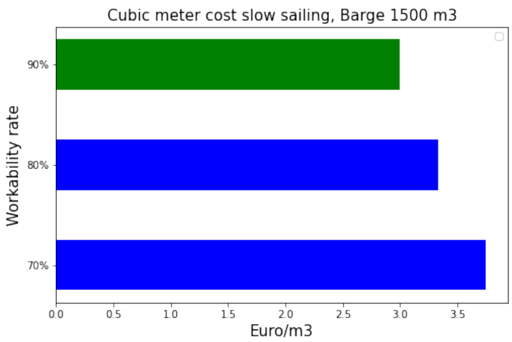


Figure 4.20: Workability influence 1500 m³ barges: €/m³

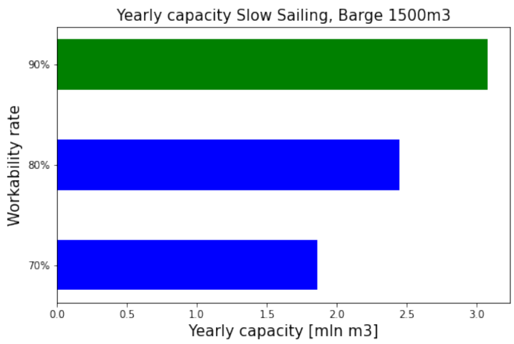


Figure 4.21: Workability influence 1500 m³ barges: yearly production

in overall cubic meter cost in case of an increase of the management cost can be seen in Figure 4.22 and Figure 4.23. Where the first Figure respectively shows the relative impact of the weekly cost increase and the latter shows the effect on the total cubic meter price. The scenario in which the management cost increases to €25000 per week shows a relative increase of 0.4 €/m^3 for the 1000 m^3 barge and a 0.25 €/m^3 price increase for the 1500 m^3 barge. The larger barge is less affected as the overall weekly cost for the 1500 m^3 barge is higher and the relative impact is thus lower.

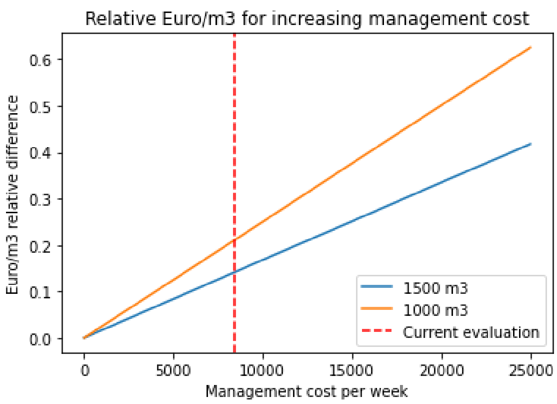


Figure 4.22: Management cost relative influence

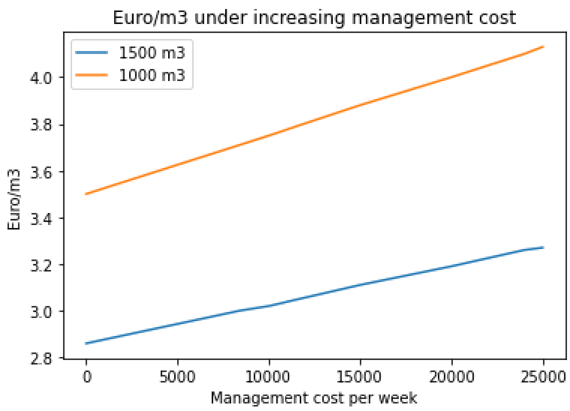


Figure 4.23: Management cost influence on cubic meter price

The second cost component that is studied is the cost of the coupling point of the pipeline from the crawler and the semi-autonomous barge. As this is a system that still needs to be developed and implemented the price might be higher than the first cost estimations provided by Sweco in Sweco (2022a). For this reason the relative impact and the overall cubic meter price impact are presented in Figure 4.24 and Figure 4.25. The cost estimate used in the cost calculations for the coupling point is €500.000. This price covers the development and the purchase of the system. The influence is researched up unto a price of 2 million euros. It must be noted that in the cost overview these exact numbers are not shown as the price is spread over the lifetime of the crawler to present weekly cost. The lifetime of the coupling point is assumed to be 7.5 years. As the investment is spread over the longer period the relative influence of the increasing cost of the coupling point is lower than that of the management cost. In case the coupling point costs 2 million euros the increase in price for the 1500 m^3 barge is 12 cents per cubic meter for the 1000 m^3 barge and 8 cents per cubic meter for the 1500 m^3 barge.

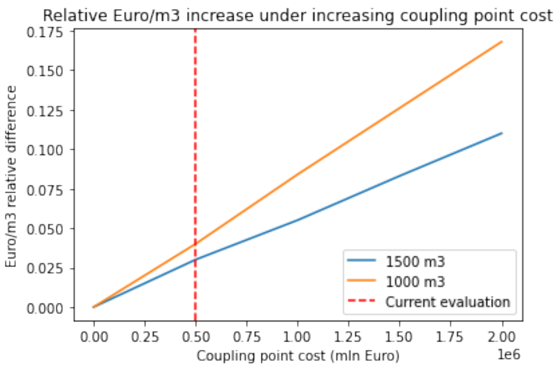


Figure 4.24: Coupling point cost relative influence

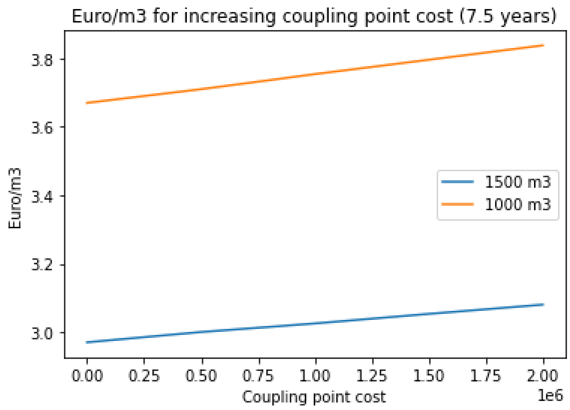


Figure 4.25: Coupling point cost influence on price per cubic meter

As a last sensitivity the price of the electricity that the crawler uses is shown. As in the management cost sensitivity Figures and the coupling point cost sensitivity Figures two plots are given that show the relative impact of the changing electricity price per kWh and the impact on the total price. In the electricity component relative influence the impact on both different sizes of the barges does not differ much. The electricity cost can thus be said to scales more evenly than the other sensitivity components. The increase in power demand for the larger barge is growing linearly and thus resulting in an evenly distributed price increase for the different kWh prices. The kWh price is shown in Chapter 2 to be the price for the electricity that is delivered to the crawler. That means that in the cost the cost for the electricity should be included as well as the cost for bringing the electricity to the crawler. Suggestions are given that this might be done with an power cable to the shore, to a windmill or in case that is not possible also a fueled engine is used. In either case the electricity price is presented as an inclusive kWh price. As these assumptions are open for volatility the electricity price is shown as a sensitivity. As the price per kWh increases the cubic meter price increases as expected and the increase is in the order of 4 cents per cubic meter increase for 0.1 €/kWh increase. This is lower than the influence of the management cost and the sensitivity of the coupling point investment cost.

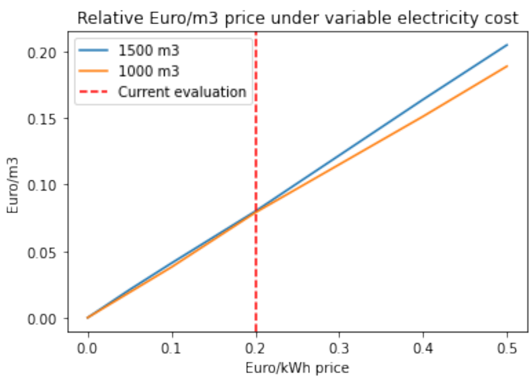


Figure 4.26: Electricity price relative influence

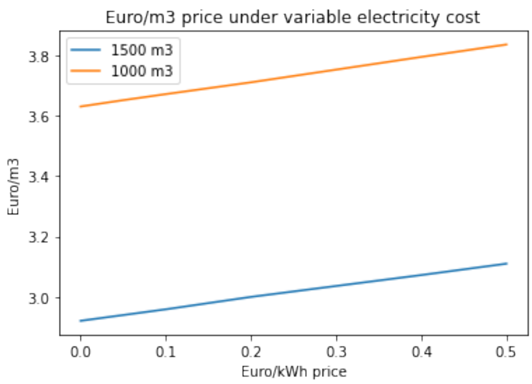


Figure 4.27: Electricity influence on price

Summary

Different sensitivities have been explored. The goal was to look at the change in cost for the Slow Sailing system under changing circumstances. Some of the changing aspects have a higher impact on the cost than others. A big decrease in the workability rate of the system has the largest potential impact on the project cost. The largest barge of 1500 m^3 shows an increase of 75 ct or 25% if the workability decreases from 90% to 70%. Furthermore, a conservative break even price for the CO2 cost was presented. As the total cost for TSHDs increases a lot more under increasing CO2 prices than the Slow Sailing system there is a good opportunity for the system as it becomes relatively cheaper.

5 Discussion

The discussion discusses the results presented in Chapter 3 and 4 and provides overall implications of the results delivered.

5.1. Feasibility

The feasibility Chapter focuses on the sailing speed of the barges and the timing in the tidal cycle. In this chapter calculations and interpretations are made that are based on available data, schematization and useful assumptions. In order to create a complete view, some of these interpretations and assumptions are listed as they are important in the interpretation of the results.

5.1.1. Environmental conditions

At first the environmental conditions that are used in Chapter 3, and also based on schematizations made in Chapter 2 is discussed. They are presented based on the tidal current and wind conditions. The winddata that is used comes from a measurement point in IJmuiden (KNMI, 2023), which is closeby the project location. However, these measurements are not directly measured at the project location and could thus differ from the actual wind conditions. The data was adapted to be a little bit above the barge height at +5 meters. As the data at +5 m was used to create Beaufort indications, there might be a slight mismatch in the data presented as windforces and what an actual weather station would indicate.

The main goal of the winddata analysis was split up into two components. The first was to find a speed for the barges to sail, so that under most of the wind conditions the barges were able to sail in a straight line through the water (V_s). The other goal of the winddata analysis was to implement the wind resistance and rudder resistance into the OpenTNSim model to be able to calculate the total energy use under different wind conditions. This was summarized in calculating a windfactor that could be used to easily calculate the energy demand under wind conditions for different sized barges and TSHD's

A critical mention to this study is that the relative influence of waves and wind was not studied. This means that although the main focus of the project was to find the influence of the wind the waves could be equally important, but are ignored. Szelangiewicz and Żelazny (2018) also shows that the wind as well as the waves influence the drifting of barges. As Bosboom and Stive (2015) shows that wind is related to the creation of drifting impacts with only the wind included can lead to an underestimation of forces on the side of the vessel. This is also shown in the similar wave- and windrose projected in Chapter 2. In addition, the interaction of the barges with higher waves at the Northsea is not considered in terms of stability, which could be relevant for the smaller barges with limited freeboard height. Furthermore, the area exposed to the wind can change due to the wave induced motion of a barge. These effects can lead to an underestimation of the minimal sailing speed as there is a possibility the barges are drifted off their course by the wave action. For reference, a typical smaller dredging vessel can operate at wave conditions conditions up to Hs = 2.5 m (Boskalis, 2010). It can be seen in Chapter 2 that waves exceeds this height approximately 10% of the time.

In order to calculate the influence of the wind on the resistances of the ship a standard setting is set to find a windfactor, which is than used to extrapolate the general runs of OpenTNSim and calculate project total energy demands by multiplying the total energy demand with the windfactor. In calculating the windfactor it is found that an anomalous situation is found under wind force 5 and 6. In these situations a smaller angle to wind must be sailed in order to sail in a straight line. Thus some flexibility is already needed in the disposal location as under heavy wind the barges will not be able to cope with big incoming wind angles. Also in calculating the windfactor, the main wind directions under all wind forces are used to calculate the energy demands. It can be seen in Appendix C that the wind with a force of Beaufort 4 actually pulls heavy on the results as it comes in under a wide angle. This creates large forces on the rudder that must be used heavily in order to keep the barge on track. As in a later stage the optimisation must be readdressed it is for now assumed that this windfactor calculation is sufficient. Although, the calculation of the windfactor is based on the Slow Sailing barges it is also used in the energy calculation of the TSHDs. As the implementation of the wind module in the OpenTNSim model does not use relative wind angles, but only real wind angles there was no separate windfactor calculated.

5.1.2. Timing

Sweco (2022b) shows that the actual tidal signal at the Dutch coast is not completely symmetrical, showing a small offset to the north. In other words barges will not be able to follow the exact timing and speeds as indicated in this research, but need to readjust a bit based on the disposal location relative to the winning location to end up in the right place. These fine readjustments need to be made in every situation and are not a direct part of the scope of this study. Some small extra speed is needed to compensate the net drifting in northward direction, this is ignored in the results of this report.

In the schematization of the dredging cycle all routing and distances were oriented on straight line sailing, ignoring inertial forces. As can be seen in Figure 5.1. Neglecting the inertial forces of a vessel can lead to two errors. The first is the assumption that the ship can physically navigate any sharp bend, when in reality, this is not possible. The second error results from neglecting the minimum turning circle of the vessel. The effects of inertial forces on the minimum turning circle have been discussed by Yasukawa and Yoshimura (2015). When the start and end locations of a project are close to each other, the vessel cannot sail in a straight line between them due to the minimum turning circle. As the ship also needs to return to its starting point, the route becomes an oval shape between the start and end points.

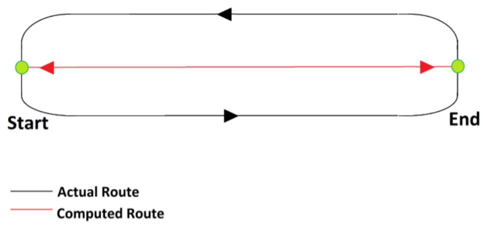


Figure 5.1: Ignoring inertia in routing (Halem, 2019)

5.2. Energy

The energy demand is one of the central parts in this study and the comparison of the energy demands of the different systems in Chapter 4 provides interesting results. In both the Slow Sailing system and the TSHD system the energy is calculated for a loaded and an unloaded path and the sum of the two is the total sailing energy demand of one cycle. To calculate the total sailing energy demand of a project, the number of cycles is multiplied by the energy demand per cycle and the windfactor. The Slow Sailing system uses smaller barges compared to the TSHD and has thus a longer project duration as is inherent to the concept. It shows under a workability rate of 90% a yearly capacity of 2 million cubic meters for the 1000 m^3 barges system and a yearly capacity of 3 million cubic meters for the 1500 m^3 barges system.

Extrapolating those numbers would require 4-6 systems operating full time along the coast to cover the entire dutch sediment demand as described in Rijkswaterstaat (2020).

5.2.1. Sailing

As the sailing energy requirement is about 45 times smaller for a barge cycle compared to a 4280 m^3 TSHD cycle the energy demand for a total project is actually closer together. This results from the barge volume being smaller and thus roughly three barges are needed to get the same amount of sediment from A to B. This results roughly in a factor 15 gain for sailing energy in favor of the Slow Sailing barges. In this study relative small TSHD's are used for comparison as the larger TSHD in this study with a volume of 4280 m^3 is actually in the 'smaller' category TSHD's when compared to what size TSHD's are available in in today's market (Blueconomy, 2010).

5.2.2. Dredging

The energy need for the dredging of the sediment is calculated in different ways for the different systems. In the Slow Sailing concept a calculation sheet from IHC that was used in earlier studies for the Sandwindmill project. This calculation sheet was adjusted to also take the height energy into account. It provides power outputs based on a pipeline diameter. It takes 3.1 hours of the full cycle for the filling of the barge in both the 1000 m^3 and 1500 m^3 barge systems. On the TSHD the power for the dredging systems is based on a set filling time of 90 minutes. The kW of the pump is than multiplied with the 1.5 hours to come to the energy demand assuming full power given. As these two methods are different in approach the higher power demand for the TSHD is not unexpected, as the power calculation of the TSHDs is based on full power use and the power of the crawler is not. As the pipelines connected to the crawler are longer than the pipelines on board the TSHD and the height elevation is equal, the energy needed for a similar size volume is actually expected to be larger for the barges as the pipeline resistance is larger.

5.3. Emissions

Emissions for the Slow Sailing barges are based on the OpenTNSim model outcomes for the CO2 estimates of a diesel engine. However, as these estimates are based on diesel engines from the year 2000 that emit CO2 they will not be used in a realistic scenario. In the desired system a different engine type would make more sense as the efficiency of diesel engines at low power rates is low. This could mean that the results obtained for a diesel engine use for slow sailing barges is actually underestimated due to lower efficiency rates at low power. However, for comparison reasons the direct emissions from OpenTNSim are used despite the efficiencies of the diesel engines being lower.

The emissions of the TSHD are based on the sailing emissions of CO2 based on OpenTNSim and the emissions related to the dredge pump. For the dredge pump a conversion rate is used from Blueconomy (2010) that links the amount of CO2 to the amount of diesel. A conversion rate of 3.18 kg CO2 / kg diesel is used. When the complete project is evaluated the CO2 of the dredge pumps is relatively larger for the larger TSHD of 4280 m^3 than for the 1580 m^3 TSHD. The complete sailing emission stays constant between the two, showing that the increase in sailing emissions for the larger TSHD is compensated by the fewer cycles that it needs to execute. The dredging energy does however increase which indicates the relatively larger dredging pump of the bigger TSHD.

5.3.1. Prices

As the minimal prices set for the CO2 are used in this project there is no volatility and the price change is linear. However EMBER (2023) shows the actual and more updated market prices for a tonne CO2 in the

European market. This reaches a price of 90 euro per tonne CO2 in April 2023. Increased CO2 prices provide increased potential for the Slow Sailing system. Also, in the Dutch government tender process the MKI is used, granting price reduction on lowering CO2 emissions as shown in Ecochain (2022). These can both be reasons for the break even price of the CO2 emissions to be achieved sooner than depicted in Chapter 4. This shows a conservative indication based on certain CO2 prices provided by the Dutch emission authority.

5.4. Cost

The cost of the Slow Sailing system and the TSHD's is reduced by increasing the size of the used vessel. This can be seen as the prices go down for the larger vessels, which originates from scaling advantages. This is the reason dredging vessels have been increasing in size. In the nearshore the advantage of smaller vessels is that they can reach further towards the cost and dispose the material in a fast and energy efficient matter (Van der Spek et al., 2007). All cost indications are estimates and are not based on first hand provided data, but publicly available data. This could indicate that the cost estimations could deviate from the provided results.

Positioning time
In Blueconomy (2010) the positioning time for the TSHD is set to be 15 minutes of 0.25 hours. This time is required to position the ship into the right location for the disposal of the sediment. This positioning is independent of the disposal method and thus present in all estimates. The Slow Sailing system uses barges that need to be precisely controlled on their path to the shore in relation to the environmental conditions. Therefore it is assumed that in this pathing the positioning can be built in and therefore no extra time is added in the cycle of the Slow Sailing system for the positioning of the barge for disposing.

Workability rate
The Slow Sailing concept and the TSHD's are both intended to operate for 90% of all time. As shown in Chapter 4 this leads to a direct cost comparison based on the same workability rates. As the project duration of the TSHD will be lower the estimated workability rate is actually expected to be higher than the workability rate of the Slow Sailing system. As the goal of the Slow Sailing system is to continuously nourish the coast it will encounter all weather conditions. Using a TSHD, the contractor can perform dredging activities in a preferred season. Thereby reducing the chance for bad weather and increasing the achievable workability rate.

Filling rate
The filling rate for both the barges and the TSHD's are set to be the same and they do not change. All vessels are assumed to be filled up with sand for 90%. In terms of sand on board that means that with the porosity of 0.4 the actual amount of sand particles is 0.9 * 0.6 = 0.54% of the on board volume in the vessels. In reality this will be related to the actual vessel characteristics and equipment. For comparison reasons it is a convenient solution to provide an equal filling rate.

Cost comparison Blueconomy
When the cost presentations are compared to Blueconomy (2010) most cost indications are alike or even directly extracted from this source. Some components differ in the comparison. The cost of rent for vessels is higher in the CIRIA than in Blueconomy, despite the source of the Blueconomy report being CIRIA. This is a salience to which no further interpretation can be given at this moment. Furthermore, the risk and profit cost are neglected in this report as that is company specific. Also, the cost in the Blueconomy report are higher as they also include the taxes.

5.4.1. Sensitivities

From the sensitivity analysis it can be seen that as multiple factors end up being more expensive the overall cost increases. However the price increases are not such that the numbers change tremendously.

The biggest impact is made by the workability sensitivity study. It has the biggest impact and shows that further workability research is needed. This makes sense as the workability rate influences the direct weekly production as well as the depreciation and interest cost. These cost are based on the total weeks that the barges sail per year, increasing the cost if the amount of weeks available decreases.

6
Conclusions & Recommendations

The conclusion and recommendations chapter provides and summarizes information based on results made in Chapters 3, 4 and 5. This Chapter concludes on research questions that were set in Chapter 1. In addition, it provides recommendations for further research to optimize the concept implementation.

6.1. Conclusions

This section presents the conclusions based on the report. The main research question is answered in 6.1.1. Sections 6.1.2 to 6.1.5 answer the sub questions.

6.1.1. Main research question

What is the gain in energy consumption, emissions and cost for the Slow Sailing concept compared to classical nourishment strategies?

Based on a nourishment project with a project size of 1.000.000 m^3 two systems are compared against each other. On one hand the Slow Sailing system using three barges and an electrical crawler and on the other hand a trailer suction hopper dredger. For both systems two volume sizes are used for comparison. The goal of the comparison is to compare the energy demands for the sailing in the dredging cycle, the total project energy demand, total emissions and cost. The Slow Sailing shows significantly lower energy demand on the sailing when compared to the TSHD. When one barge is compared to one TSHD for one dredging cycle it uses 45 times less sailing energy. This means that to use a full cycle of the Slow Sailing actually this factor needs to be divided by three as there are three barges in use. This means roughly a factor 15 decrease in sailing energy demand for the sailing component of the dredging cycle.

Two TSHD size and two barges sizes for the Slow Sailing concept are further used for comparison. The 1000 m^3 and 1500 m^3 barge sizes are chosen and the 1580 m^3 and 4280 m^3 TSHD sizes. The 1000 m^3 barge is chosen as it is given as an entry point for this study and therefore a reference to earlier studies. The 1500 m^3 barge is chosen as it is a larger barge size that is able to be filled with the capacities of the used crawler. The 1580 TSHD is chosen as a more direct comparison to the 1500 m^3 barge and the 4280 m^3 TSHD is chosen as it is a more accurate description of what is actually used currently. In this full project also the local wind conditions are considered and a windfactor is used. The TSHD shows an additional 1000 tonnes CO2+ emission in this complete project. This is for CO2 emissions of the sailing and for the dredge pump. The cost are most favourable for the 4280 m^3 TSHD with a 2.55 €/m^3 price exclusive taxes. The most beneficial Slow Sailing system is with the barges of 1500 m^3. This results in 3.00 €/m^3 for the project. When the energy of the complete project is compared the crawler energy and the pumping energy are included. For a complete project the results shows differences of a factor 4 in energy use of around 0.5 kWh/m^3 for the Slow Sailing system compared to the 2 kWh/m^3 for the TSHD. Thus the Energy use and CO2 are favourable for the Slow Sailing system compared to the traditional TSHD dredging strategy. However, in this comparison the lower emissions and fuel cost do not fully cover the price as the TSHD with 4280 m^3 is the cheapest strategy.

6.1.2. Environment

What environment is the system implemented in and how can this be schematized?

The Slow Sailing concept is tested and conceptualized for the Northsea area along the dutch coast. To specify the area the Noord-Holland coastline is treated and a general dutch coastal depth profile is set. This area is in permanent demand for sand as it is subjected to sea level rise. Along the dutch coast multiple yearly nourishment campaigns are worked out because of this. The exact location of these projects is varying and is adjusted to tilt specific eroding zones up to the base coast line level.

The system is placed in the Northsea and therefore exposed to its local environmental conditions. The dynamic system in which, wind, waves and current play a role is schematized. The tidal current is simplified to a symmetrical tidal velocity signal. The wind conditions are take set to be constant for the sailing duration of the barges and the wave influence is ignored.

6.1.3. Components

What components are in an operating Slow Sailing system and how will they interact to create a complete system?

The Slow Sailing system consists of multiple separated system components. This is also one of the main differences to classical nourishment strategies. In this study 3 barges continuously nourish the coast, these barges can vary in size and volume. They sail from and towards the coast in a constant matter. At each moment in time one barge is filled, one barge sails towards the shore loaded and one barges sails back to the winning location unloaded. The timing for the barges to sail is aligned to the tidal cycle. At the winning point the barges are filled by an electrical crawler that is on the bottom of the Northsea and pumps a soil-water mixture up a pipeline. The crawler has a maximum capacity of 1350 m^3 per hour. The energy demand of the crawler is met by a connection to shore or to a windmill. A pipeline reaching from the crawler will be coupled to a barge in order to fill a barge by a coupling point above the water level.

6.1.4. Feasibility

How can you analyze the feasibility of the Slow Sailing concept in this area based on local wind and tidal conditions?

This feasibility study focuses on the workability for sailing in the local conditions. In order to sail in the Northsea conditions the barges need a minimum sailing speed. This minimum sailing speed is based on the local wind conditions and the tidal influence. The barges need to be able to provide a countering moment to the wind blowing the barge away from its desired sailing path. Steering creates this moment that ensures the barges are able to sail in a straight line. A sailing speed of 1.2 m/s or 2.3 kn is set as it provides sufficient workable conditions. Thereby, the timing in the tidal cycle in this system is adjusted in order to counter the tidal motion as little as possible. The barge will leave the winning station after 3.1 hours and sails towards the shore in 3.1 hours. The first 1.55 hours it is drifted in Northward direction and the second 1.55 hours it is drifted Southward. This symmetry in the tidal velocity channel is used to end up in the same location in the alongshore direction. On the way back the barge must sail a bit faster as the next 3.1 hours in the tidal cycle will drift it only southward. Therefore the speed is increased to 1.7 m/s to ensure the barge ends up at the winning location again and it can restart its cycle.

6.1.5. Cost components

What are cost components in the Slow Sailing system and how do they compare to classical nourishment strategies?

The different cost components related to the Slow Sailing system are:

- Vessel cost
- Sounding vessel cost
- Execution cost
- System component cost
- Energy, fuel and emissions cost
- Overhead cost

The vessel cost includes the depreciation and interest, the maintenance and repair, insurance and crew cost. The cost for the barges is lower than the cost for the TSHDs. The three barges of 1500 m^3 are cheaper than the weekly cost of the 1580 m^3 TSHD. The main difference is the depreciation and interest cost and the management personnel cost. The sounding vessel and the execution cost are equal for the Slow Sailing system and the TSHD's. An additional cost component for the Slow Sailing is the system component cost, related to the crawler, pipeline and coupling point. The energy cost is a factor 3 lower for the Slow Sailing system. The overhead cost is a percentage of the total cost and thus a good indicator for comparison.

6.2. Recommendations

As the system shows high potential it is recommended to look for further ways of improving the concept before implementing a system. Specifics in time, number of simultaneous running systems and implementation strategy can further lower the cost and make the results become even more promising. Further implementation explorations and underlying research advised is given.

6.2.1. Barges

The results for the different scenario's are based on the model OpenTNSim that provides resistances, energy, diesel and CO2 emissions (Jiang et al., 2022). In this phase of exploring the Slow Sailing concept standard barges are used as provided in CIRIA (2009). They are to be run by diesel engines and the diesel use and emissions are based on a diesel engine type build in the year 2000. A scenario in which the Slow Sailing concept can be implemented will be in the mid 2020's and the barges will be made to fit. This means that custom made barges will be used in the system that can be optimized for project specific tasks. It is recommended in the design of these new barges to dive deeper into some of the design aspects of these new build barges:

Engine type
The engine type is a big part of the barge and is important in terms of cost of the barge as well as its viability for Slow Sailing conditions. Research could explore the various types of engines that are suitable for Slow Sailing conditions, and compare their efficiency and effectiveness in these scenarios. New studies could review the different types of propulsion systems commonly used in Slow Sailing conditions, comparing diesel engines, electric motors, hybrid systems and new systems, such as hydrogen or ammonia. These new types are currently under research for implementation in shipping industries as for example de Vos (2020) shows. The impact of putting these type of engines in Slow Sailing barges is still to be looked at. It could discuss the advantages and disadvantages of each system, including their fuel efficiency, reliability, and environmental impact.

It must be noted that in case of the implementation of an Eco-friendly engine the emissions will be significantly lower. This can be said for the barges as well as a general dredging vessel. It can be seen that different engine types as replacement for regular diesel engines on board dredging vessels are also options in the innovation for dynamic coastline preservation program (Rijkswaterstaat, 2022), such as the LEAF Hopper that uses an hydrogen engine by Royal IHC (IHC, 2021).

Hotel options
The financial impact of building a semi-autonomous barge is influenced by multiple design factors. One is the loss for necessity of hotel options on barges. It is recommended to research the change in design for new designed semi-autonomous barges as the neglected hotel options can be used to accommodate more space on a barge for loading capacity. This could influence not only the initial investment, but also the carrying capacity of the loaded barges increasing the productivity.

6.2.2. Further environmental research

As requested by Sweco this study focuses on mainly on the wind and current impacts on the barges. As the direct environmental climate is also greatly influenced by the waves. Rijkswaterstaat (2020), and Szelangiewicz and Żelazny (2018) show that the wave forcing and direction also influence the turning moment created on a barge. It is advised to combine these effects of waves and winds for the Northsea conditions. Furthermore, the effect of the assumption of the symmetrical tidal velocity signal should be considered. It is recommended to research the impact of the asymmetry and neap/ spring cycle on the timing of the sailing barges and the resulting energy demand changes.

In addition, in case of implementation of the system the local sand system should be studied with more care as it can be a big influence on the practical implementation of the system. This holds for direct disposal locations that decide the routing and the spread of the material across a sand deficient zone. In this report a disposal and mining location are picked based on the rough positions in which mostly the distance between two points, the orientation perpendicular to the coastline and the rough designated places. The actual locations and spread should be picked with more in depth knowledge on the berm area (Van der Spek et al., 2007). The area, as it also influences the spread of materials and can show beneficial behaviour when carefully picked as Van Duin et al. (2004) showed that existing sand bars could move towards the shore and increase in height.

6.2.3. System equipment

Besides the barges the Slow Sailing concept is characterised by the decoupling of tasks in the system. This means that different components work at different locations at the same time. As the system is depending on all these separate components, all different parts of the system must be assessed and researched for reliability and performance.

Crawler
As Sweco did earlier research into the crawler it is known that a subdredge is used at the moment for specific dredging tasks up unto a depth of 50 meters. However, at this moment it is only known that the subdredge is available and can be used for long distances to shore. This comes from the Sandwindmill concept research (Sweco, 2022b). The original 12 km pipeline combined with the subdredge proposed a system in which the pipeline is fully submerged on the bottom of the Northsea all the way from the winning location to the shore. Also it needs to be researched if a final system is chosen if the crawler capacity (1350 m^3/hour) is actually viable based on the speed and drag caused by the moving of the pipeline. Also, the stability by wave forcing at the seabed should be considered.

Pipeline
In the slow-sailling concept it must be researched what the implementation of a vertical pipeline towards a buoy does with the workability. Wave action in the Northsea might be a complicating factor for the pipeline stability as waves tend to generate more forcing and variations at the waterline (Bosboom and Stive, 2015).

6.2.4. System opportunities

This report sketches a system in which the Slow Sailing concept is showed, tested and compared to classical nourishment strategies. In practise this means that the current comparison is based on a classic dredging project as it could be issued by Rijkswaterstaat for a one time project. However, the concept of Slow Sailing allows for broader and creative thinking and exploring beyond the current methods used by Rijkswaterstaat. It can fit in with future nourishment strategies by providing flexibility and fits in with scaling opportunities and needs.

Up-scaling

One benefit of the Slow Sailing concept is that the remote controlling of the barges enables to easily scale the system up in terms of execution. Multiple projects could be carried out at the same time at different locations, while the personnel used to overview the system in the control room stays equal. This could reduce the cost per cubic meter per project as the relative personnel requirement is reduced. As in the scenario shown in Chapter 4 showed that the personnel weight of the cost is around 10%, half being the operational cost. A first estimate could argue that the operational part of the personnel cost, could be halved resulting in a personnel cost weight of around 7.5%. A schematic example is given in Figure 6.1, wherein 4 simultaneous projects are in execution at different locations along the dutch coast.

Figure 6.1: Increasing the number of Slow Sailing systems running simultaneously

Tidal motion gains

Another exploitable use of the concept is in using the tidal motion on the Northsea for transport in alongshore direction. If the scope of a project is shifted in carrying sand from one winning location towards multiple locations along the coast the system can be adjusted so that the tidal current can take care of the alongshore transportation. The barges sail mostly towards the shore. In this implementation the workability based on rudder compensation should be revised as the speed through water should still be sufficient to prevent the barges from drifting. Another choice herein is to let the barges drift and be carried around by the natural elements. In this implementation real time decision making is required for the barges that sufficiently projects the influences of drifting, direction and manoeuvrability. As the orientation of these barges can change, due to being rudderless. Natural forces will act in maximal force lowering the energy demand of the barges, but the resilience and options for manoeuvring the barge will decrease.

Figure 6.2: Slow Sailing system with multiple disposal locations making use of the tidal motion for alongshore transport

Disposal location optimalization

In the current project the windfactor that is used to calculate energy demands and CO2 emissions is based on one direction of sailing through the water, perpendicular to the coastline. Energy demands and thus emissions can be lowered if the exact sailing direction is based on local and accurate wind projections for the coming hours. In that case not just the up-and-down sailing route is an option, but an optimized direction that minimizes the wind and/or wave impact for the loaded and unloaded parts combined. If the spread of the disposal location along the coast is large enough, each barge could identify the least energy demanding route per cycle.

Figure 6.3: Slow Sailing system with large flexibility in disposal location to use real time decision making to use least amount of energy

Using residual flow

Sweco (2022a) showed the residual flow of the tidal current along the dutch coast. It shows a northward residual flow, due to the slight asymmetry in the tidal current signal. A system with more moving components can be researched to utilize this principle. It would contain multiple barges sailing back and forth from the winning zone westward of the -20 m depth contour towards the nearshore for a disposal. As the barges sail up and down the crawler and anchoring buoy could move up slowly as well along with the barge that sails towards the coast and back and is moved slowly north by the residual flow of the tidal current. As it reaches the end of the dutch coast it sails back towards the starting location in the south. A possibility for the sailing back towards the south is anchor during the times the tidal current is coming towards the barge to only sail with ebb tide, carrying the barge back along the coast. The focus of this implementation would be to cover multiple areas that have needs for nourishing at once or even the entire coast. In this implementation the crawler should be fit to travel larger distances. It should be monitored more intensely as a larger risk for collision with multiple moving objects is present, as the system will inevitably travel along the busy shipping crossings along the coast.

Figure 6.4: Slow Sailing system with moving winning point and disposal location using the residual flow of the tidal velocity

Combination with sandwindmill

Sweco also explored the sandwindmill concept (Sweco, 2022b). Combined elements of both concepts could be used to enhance the performance of the separate concepts. The energy provided for the crawler is in this concept provided by windmill. The sandwindmill concept researched by In the sandwindmill concept Sweco introduced a windmill that was solely used for providing energy in a nourishment system. It looked at an underwater pipeline from the mining location towards the nearshore disposal location. In the combination with the Slow Sailing project the size of the windmill should be researched as the energy demands are lower compared with the pipeline resistance in the sandwindmill concept. The additional investment cost for the placing of a windmill should also be studied. In this implementation the pipeline length and freedom of the crawler influences the durability and the business case of the system as the windmill is not easily moved.

Figure 6.5: Sandwindmill combination with Slow Sailing

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A OpenTNSim theory

This Appendix contains two parts. In the first part the OpenTNSim model is explained and in the second part an overview is presented of the input that was used for the OpenTNSim model.

A.1. Model overview

The OpenTNSim model uses the Holtrop and Mennen method (Holtrop and Mennen, 1982). The Holtrop and Mennen method is a commonly used approach for calculating the total resistance of ships. This method takes into account a range of factors that contribute to the resistance of a ship, including the shape of the hull, the size of the vessel, and the characteristics of the water it is moving through. There are several key components to the Holtrop and Mennen method:

- Hull Form Factor: This factor takes into account the shape of the ship's hull, including its length, beam, and draft. It is expressed as a ratio of the actual wetted surface area of the hull to the surface area of a "reference" hull with the same length, beam, and draft.
- Viscous Resistance Coefficient: This factor represents the resistance due to the friction between the hull and the water it is moving through. It takes into account the viscosity of the water, the speed of the ship, and the roughness of the hull surface.
- Appendage Resistance Coefficient: This factor represents the resistance due to any additional structures or features on the hull of the ship, such as propellers, rudders, or bow thrusters.
- Form Factor Coefficients: These coefficients take into account the effect of the shape of the hull on the resistance of the ship. They are calculated based on the length, beam, and draft of the ship.
- Froude Number: This factor represents the ratio of the speed of the ship to the speed at which waves propagate through the water. It takes into account the effect of the ship's speed on the resistance it experiences.

By combining these components, the Holtrop and Mennen method allows to accurately predict the resistance of a ship and the power required to move it through the water. This information is essential for designing efficient and effective vessels that can operate at maximum performance while minimizing fuel consumption and environmental impact.

In the OpenTNSim model, power is calculated based on the resistances encountered by the ship as it moves through the water. The model takes into account several different types of resistance, including frictional resistance, wave-making resistance, and appendage resistance.

- Frictional resistance is the force that opposes the motion of the ship due to the friction between the hull and the water. It is calculated using the Manning-Strickler method, which takes into account the wetted surface area of the hull, the speed of the ship, and the roughness of the hull surface.

- Wave-making resistance is the force that opposes the motion of the ship due to the waves generated by its movement through the water. It is calculated using the Holtrop and Mennen method, which takes into account the shape of the hull, the size of the vessel, and the characteristics of the water.
- Appendage resistance is the force that opposes the motion of the ship due to any additional structures or features on the hull, such as propellers, rudders, or bow thrusters. It is calculated using a combination of empirical formulas and experimental data.

Once these different types of resistance have been calculated, they are combined to give the total resistance encountered by the ship. The power required to overcome this resistance is then calculated using the following Equation. This formula takes into account the fact that the power required to move a ship through the water increases as the speed of the ship increases. By accurately calculating the different types of resistance encountered by the ship and combining them to find the total resistance, the OpenTNSim model can provide an accurate estimate of the power required to operate the vessel under different conditions.

Power = Total Resistance x Ship Speed

In the OpenTNSim model, energy is calculated based on the power required to move the ship and the time over which this power is applied. Specifically, the model calculates the amount of energy consumed by the ship's engines based on the power required to overcome the total resistance encountered by the ship, as calculated using the methods I described earlier, and the duration of the ship's voyage.

To calculate the amount of energy consumed by the ship, the OpenTNSim model uses the following Equation. This Equation takes into account the fact that the energy consumed by the ship's engines is directly proportional to the power required to overcome the resistance encountered by the ship, and the duration of the voyage. By accurately calculating the power required and the duration of the voyage, the OpenTNSim model can provide an accurate estimate of the amount of energy that will be consumed by the ship.

Energy Consumption = Power Required x Time

The energy consumed by the ship can be expressed in different units, such as joules, kilowatt-hours (kWh), or megajoules (MJ), depending on the specific needs of the user. The unit of energy used in the OpenTNSim model can be specified by the user during the simulation setup.

The calculation of diesel fuel consumption in the OpenTNSim model is based on the power required to move the ship and the efficiency of the ship's engines. Specifically, the model calculates the amount of fuel consumed by the ship's diesel engines based on the power required to overcome the total resistance encountered by the ship, as calculated using the methods described earlier. The efficiency of the ship's engines is taken into account by using a parameter known as the specific fuel consumption (SFC), which represents the amount of fuel consumed by the engines per unit of power produced. The SFC is typically measured in grams or kilograms of fuel consumed per kilowatt-hour of power produced. To calculate the amount of diesel fuel consumed by the ship's engines, the OpenTNSim model uses the following formula:

Diesel Fuel Consumption = Power Required / Engine Efficiency x SFC

The calculation of CO2 emissions in the OpenTNSim model is based on the amount of diesel fuel consumed by the ship's engines, as calculated using the method I described earlier, and the carbon content of the fuel. To calculate the amount of CO2 emissions generated by the ship, the OpenTNSim model uses the following formula:

CO2 Emissions = Diesel Fuel Consumption x Carbon Content of the Fuel

The carbon content of the fuel is typically measured in terms of the amount of carbon dioxide generated per unit of fuel consumed, such as grams of CO2 per kilogram of fuel. This value can vary depending on the type and quality of the fuel being used. Once the CO2 emissions have been calculated, they can be expressed in different units, such as grams or kilograms of CO2 emitted per kilometer traveled, depending on the specific needs of the user. The unit of CO2 emissions used in the OpenTNSim model can be specified by the user during the simulation setup.

A.2. Inputs OpenTNSim

The inputs used for the simulations in the OpenTNSim model.

Vessel	Loaded	Volume	L	B	Height	D loaded	D unloaded	Freeboard loaded	Freeboard unloaded	Propulsion power	Block factor	Speed
		m3	m	m	m	m	m	m	m	kW	[-]	kn
B1.2L700	Loaded	700	50	9	4	3,6	2	0,4	2	530	0,8	2,3
B1.2L850	Loaded	850	55	10	4	3,6	2	0,4	2	700	0,8	2,3
B1.2L1000	Loaded	1000	62	11	4	3,45	2	0,55	2	750	0,8	2,3
B1.2L1500	Loaded	1500	65	12	4,4	3,85	2,35	0,55	2,05	1050	0,8	2,3
B1.2L2000	Loaded	2000	82	14	6	4,2	3	1,8	3	1450	0,8	2,3
B1.7L700	Loaded	700	50	9	4	3,6	2	0,4	2	530	0,8	3,3
B1.7L850	Loaded	850	55	10	4	3,6	2	0,4	2	700	0,8	3,3
B1.7L1000	Loaded	1000	62	11	4,4	3,85	2	0,55	2,4	750	0,8	3,3
B1.7L1500	Loaded	1500	65	12	4,4	3,85	2,35	0,55	2,05	1050	0,8	3,3
B1.7L2000	Loaded	2000	82	14	6	4,2	3	1,8	3	1450	0,8	3,3
B1.2U700	Unloaded	700	50	9	4	3,6	2	0,4	2	530	0,8	2,3
B1.2U850	Unloaded	850	55	10	4	3,6	2	0,4	2	700	0,8	2,3
B1.2U1000	Unloaded	1000	62	11	4,4	3,85	2	0,55	2,4	750	0,8	2,3
B1.2U1500	Unloaded	1500	65	12	4,4	3,35	2,35	1,05	2,05	1050	0,8	2,3
B1.2U2000	Unloaded	2000	82	14	6	4,2	3	1,8	3	1450	0,8	2,3
B1.7U700	Unloaded	700	50	9	4	3,6	2	0,4	2	530	0,8	3,3
B1.7U850	Unloaded	850	55	10	4	3,6	2	0,4	2	700	0,8	3,3
B1.7U1000	Unloaded	1000	62	11	4,4	3,85	2	0,55	2,4	750	0,8	3,3
B1.7U1500	Unloaded	1500	65	12	4,4	3,85	2,35	0,55	2,05	1050	0,8	3,3
B1.7U2000	Unloaded	2000	82	14	6	4,2	3	1,8	3	1450	0,8	3,3

Table A.1: Input table barges

Vessel	Loaded	Volume	L	B	Height	D loaded	D unloaded	Freeboard loaded	Freeboard unloaded	Pump power	Propulsion power	Block factor	Speed
		m3	m	m	m	m	m	m	m	kW	kW	[-]	kn
TL900	Loaded	900	62	10	4	3,4	3,18	0,6	0,82	350	900	0,8	10
TL1125	Loaded	1125	65	11	4,15	3,75	2,15	0,4	2	450	1570	0,8	10
TL1580	Loaded	1580	79	14	4,35	3,35	2,35	1	2	750	2000	0,8	11
TL2500	Loaded	2500	85	15	7,7	6,5	5,7	1,2	2	1300	3000	0,8	11
TL4280	Loaded	4280	91	19	8	6,8	5,9	1,2	2,1	3000	9400	0,8	12
TU900	Unloaded	900	62	10	4	3,4	3,18	0,6	0,82	350	900	0,8	10
TU1125	Unloaded	1125	65	11	4,15	3,75	2,15	0,4	2	450	1570	0,8	10
TU1580	Unloaded	1580	79	14	4,35	3,35	2,35	1	2	750	2000	0,8	11
TU2500	Unloaded	2500	85	15	7,7	6,5	5,7	1,2	2	1300	3000	0,8	11
TU4280	Unloaded	4280	91	19	8	6,8	5,9	1,2	2,1	3000	9400	0,8	12

Table A.2: Input table TSHD

B

Windanalysis

This Appendix consists of three parts, all related to the wind in the Northsea at the project location.

B.1. Windanalysis IJmuiden

Per Beaufort the wind angle distributions are given in this Section.

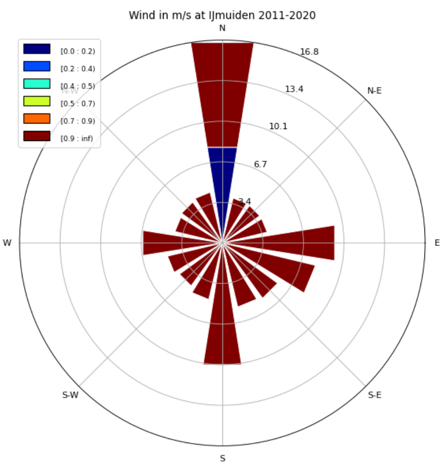

Figure B.1: *Bft1, main direction N*

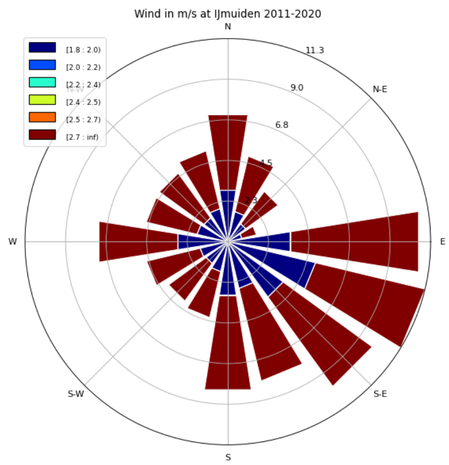

Figure B.2: *Bft2, main direction E/SE*

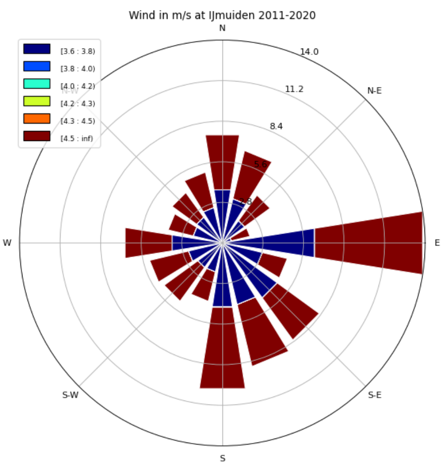

Figure B.3: *Bft3, main direction E/S*

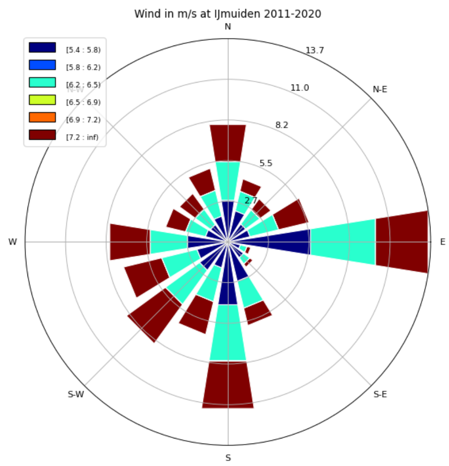

Figure B.4: *Bft4, main direction E/S*

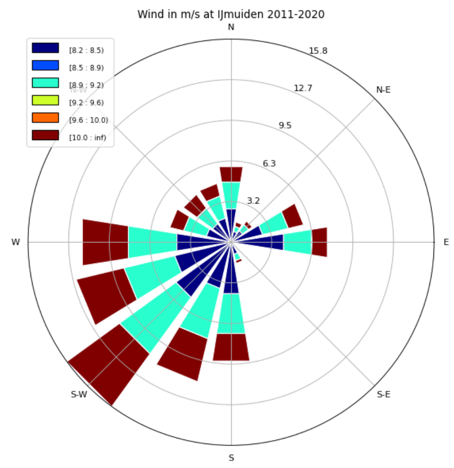

Figure B.5: *Bft5, main direction SW*

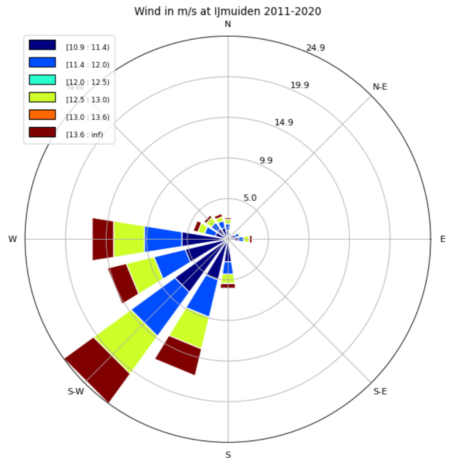

Figure B.6: *Bft6, main direction SW*

B.2. Moment compensation

This Chapter shows the possible rudder moments created by the sailing of the barges. The maximum angle of the rudder is set at 60 degrees. This shows the rudder moment compensation for in increasing wind speeds under different incoming angles. The Figures provide loaded and unloaded sailing conditions and increasing sailing speeds.

Loaded compensation

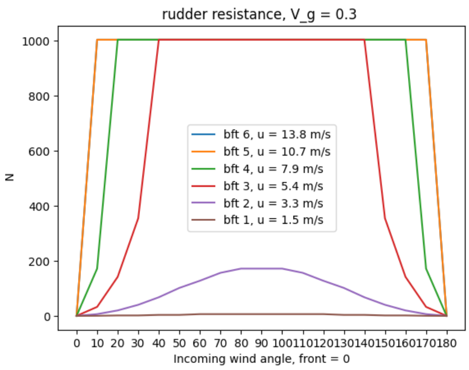

Figure B.7: *Rudder resistance, V = 0.3 m/s*

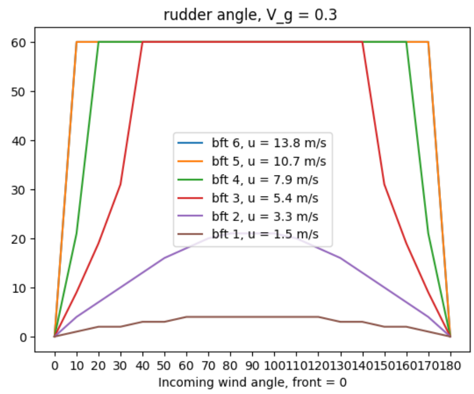

Figure B.8: *Rudder angle, V = 0.3 m/s*

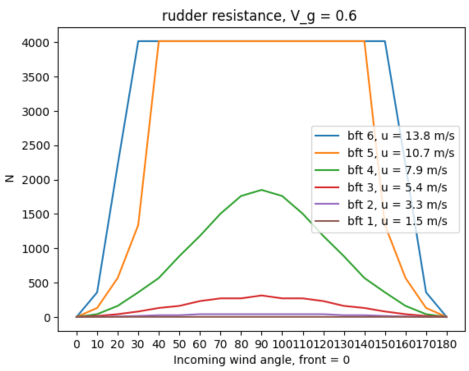

Figure B.9: *Rudder resistance, V = 0.6 m/s*

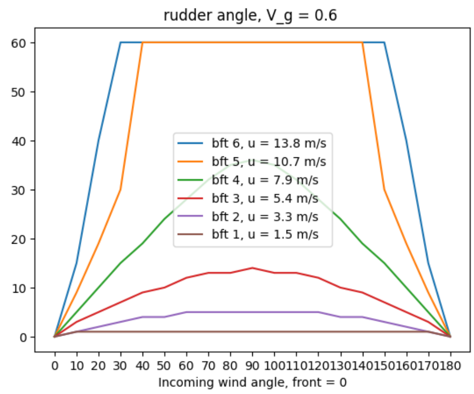

Figure B.10: *Rudder angle, V = 0.6 m/s*

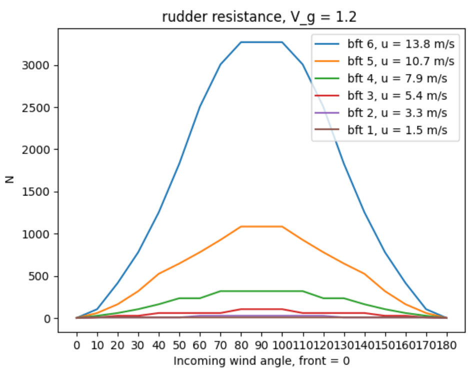

Figure B.11: *Rudder resistance, V = 1.2 m/s*

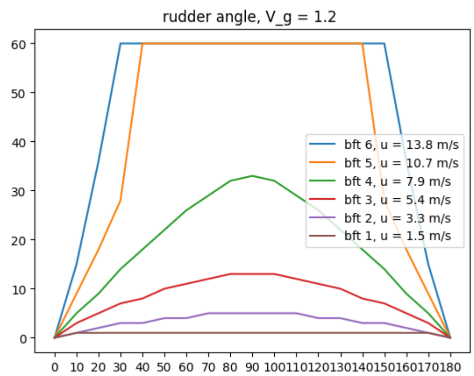

Figure B.12: *Rudder angle, V = 1.2 m/s*

Unloaded compensation

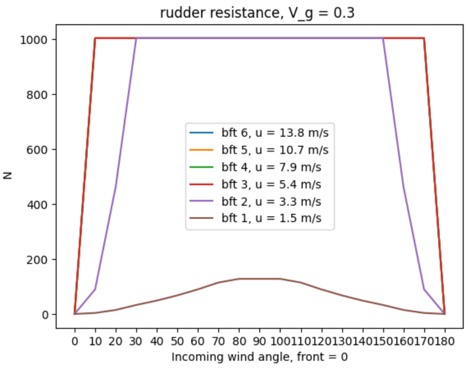

Figure B.13: *Rudder resistance, V = 0.3 m/s*

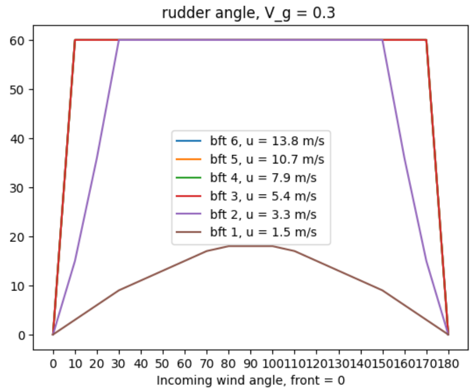

Figure B.14: *Rudder angle, V = 0.3 m/s*

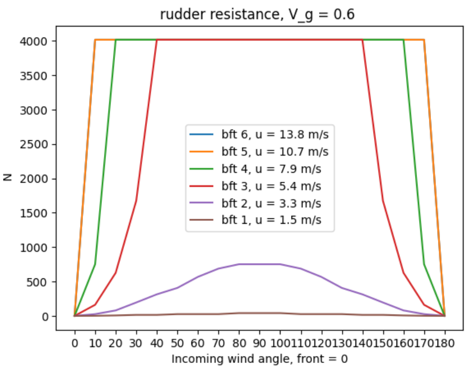

Figure B.15: *Rudder resistance, V = 0.6 m/s*

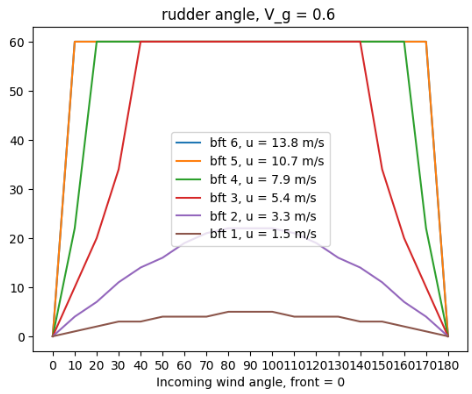

Figure B.16: *Rudder angle, V = 0.6 m/s*

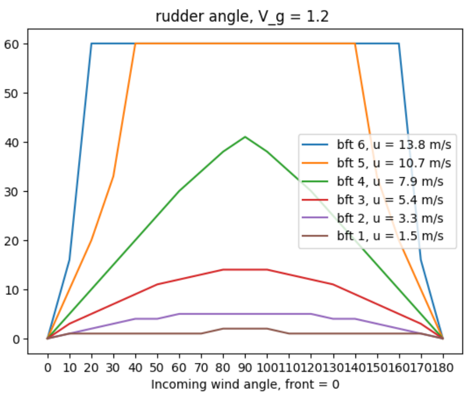

Figure B.17: *Rudder resistance, V = 1.2 m/s*

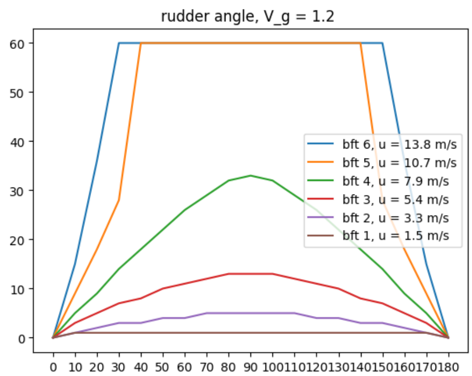

Figure B.18: *Rudder angle, V = 1.2 m/s*

B.3. Windfactor

This Section provides in Table B.1 the way the windfactor is set up. The calculation scheme is first provided in Figure B.19.

Figure B.19: calculation scheme windfactor

Windfactor (no large angles bft5,bft6)

Beaufort	Wind	Angle	Percentage	loaded/unloaded	kWh	Co2	Bft percentage	Angle percentage	Share kWh
0	0	0	0	Loaded	22	18193	0	0	0
1	1,5	90	100	Loaded	22,3	18193	2	2	44,6
2	3,3	0	30	Loaded	22,6	18340	13	3,9	88,14
	3,3	20	40	Loaded	22,8	18515	13	5,2	118,56
	3,3	40	30	Loaded	22,7	18407	13	3,9	88,53
3	5,4	0	60	Loaded	22,9	18624	22	13,2	302,28
	5,4	90	40	Loaded	22,6	18331	22	8,8	198,88
4	7,9	90	45	Loaded	24,2	19696	30	13,5	326,7
	7,9	0	55	Loaded	23,6	19143	30	16,5	389,4
5	10,7	180	50	Loaded	20,8	16863	19	9,5	197,6
	10,7	160	50	Loaded	18,6	15075	19	9,5	176,7
	10,7	140	0	Loaded	19,8	16106	19	0	0
6	13,8	180	100	Loaded	19,7	15996	11	11	216,7
	13,8	160	0	Loaded	17	13845	11	0	0
	13,8	140	0	Loaded	20,9	16963	11	0	0
Totaal								97	2148,09

Beaufort	Wind	Angle	Percentage	loaded/unloaded	kWh	Co2	Bft percentage	Angle percentage	Share kWh
0	0	0	0	Unloaded	16	12779	0	0	0
1	1,5	90	100	Unloaded	16	12779	2	2	32
2	3,3	180	30	Unloaded	14,8	12038	13	3,9	57,72
	3,3	160	40	Unloaded	13,4	10846	13	5,2	69,68
	3,3	140	30	Unloaded	13,2	10723	13	3,9	51,48
3	5,4	90	60	Unloaded	21,6	17554	22	13,2	285,12
	5,4	180	40	Unloaded	13,5	10972	22	8,8	118,8
4	7,9	180	55	Unloaded	11,1	9032	30	16,5	183,15
	7,9	90	45	Unloaded	56,6	45962	30	13,5	764,1
5	10,7	0	50	Unloaded	25,9	21004	19	9,5	246,05
	10,7	20	50	Unloaded	55,2	44929	19	9,5	524,4
6	10,7	40	0	Unloaded	153,5	123295	19	0	0
	13,8	0	100	Unloaded	32,7	26530	11	11	359,7
	13,8	20	0	Unloaded	109	88546	11	0	0
	13,8	40	0	Unloaded	172,7	137976	11	0	0
									2692,2

Total	Reference	Factor
4840	3800	1,27

Table B.1: Windfactor calculation

C

External input

C.1. Price indexations

The price indexations as used in calculating the cost per week in the different scenario's are presented in this Table. As a lot of the data originates from 2009, the Ciria indexation version of 2021 is used in multiple cases (CIRIA, 2021). For the transition of 2021 to 2022 the central bureau of statistics (CBS) in the Netherlands has been consulted. It shows from 2021 to 2022 an increase of 4 percent of the production prices for the construction industry, specifically for the machinery in soil excavation CBS (2023). These indexations are used for all components.

	Price year	Indexation	Source	Note
Barges	2009	1,175	Ciria, CBS	1,13 2021, 1.04 2022
TSHD	2009	1,175	Ciria, CBS	1,13 2021, 1.04 2022
Personnel	2022	0	van Rhee	
Crawler	2022	0	Indications Sweco	
Diesel	2023	0	International diesel market	
Emissions	2022	0	Dutch emission authority	
Energy crawler	2022	0	Indications Sweco	
Pipeline	2009	1,175	Ciria, CBS	1,13 2021, 1.04 2022
Coupling piece	2022	0	Indications Sweco	
Conversion rate	2023	0	Dollar to euro	
Barges transformation	2022	0	Indications Sweco	
Sounding vessel	2009	1,175	Ciria, CBS	1,13 2021, 1.04 2022
Personnel vessel	2009	1,175	Ciria, CBS	1,13 2021, 1.04 2022
Execution cost	2009	1,175	Ciria, CBS	1,13 2021, 1.04 2022

Table C.1: Indexation prices

C.2. Dieselprice

Table C.2 shows the conversion from market prices to diesel prices per liter Ship&Bunker (2023).

400	$/mt	IFO380
372	euro/mt	IFO380
0,37	euro/kg	IFO380
0,44	euro/L	IFO380

*based on 0,84 kg/L

Table C.2: Diesel price conversion to euro per Liter

C.3. Crawler energy demand calculation

Table overview of calculation scheme for crawler energy demand. The calculation is based on the summation of the pipeline resistance and the height elevation. A safety factor of 50% is used in order to gain a solid energy demand. Equations used in the spreadsheet are depicted next to it. The spreadsheet is a modified spreadsheet after an original spreadsheet was made by IHC in exploration of the Sandwindmill.

		1500 m3	1000 m3
Project size	[Mm3]	1	1
Transport distance	[km]	0,2	0,2
Calculation results			
Production system	[m3/jaar]	1.660	1.190
Power	kW	75	55
Needed production	[m3/y]	1.500	1.000
Inputs			
Input parameter	Unit	Value	Value
Water density	[kg/m^3]	1.025	1.025
Water dynamic viscosity	[Pa.s]	0,00132	0,00132
Particle diameter (d_{mf})	[mm]	0,310	0,310
Solids density	[kg/m^3]	2.650	2.650
In-situ density	[kg/m^3]	1.900	1.900
Volume concentration, real	[%]	15,0%	15,0%
Corresponding mixture density	[kg/m^3]	1269	1269
Volume concentration, situ	[kg/m^3]	28%	28%
Transport pipe inner diameter	[mm]	400	350
Transport pipeline length	[m]	200	200
Cross-section area discharge pipe	[m2]	0,13	0,10
Transport factor	-	0,95	0,95
Delivered concentration (Cvd)	[%]	14%	14%
Critical velocity	[m/s]	3,43	3,21
Safety factor	[-]	1,3	1,3
Design velocity transport system	[m/s]	4,46	4,17
Total mixture flow	[m3/s]	0,56	0,40
Solids flow, actual	[m3/s]	0,08	0,06
Solids flow, situ	[m3/s]	0,15	0,11
Reynold number	[-]	1.385.285	1.133.838
Eps, pipe wall roughness	[mm]	0,03	0,03
Friction factor (Lambda)	[-]	0,012745026	0,013141929
Pressure drop	[bar]	0,80	0,83
Pump efficiency (losses)	[%]	60%	60%
Indicative total pump power required	[kW]	75	55
Effective pump head	bar	25	25
Pumps required	-	1	1
Afstand tussen pompen	[m]	200	200
Power efficiency	%	75%	75%
Power required from turbine	MW	0,20	0,10
Hourly production	situ m3/hr	534,5	382,8
Weekly	hr/wk	3,1	3,1
Energy per year	kWh	233	172
Cycles per barge		247	370
Barges		3	3
Energy/project	kWh	172571	190902
Production per cycle	situ m3	1.660	1.190
Particles sand per cycle	m3	893	640
Energy Height mgh	Joule	2,08519E+12	2,08519E+12
	Joule = 1 KWh	36000000	36000000
Total energy	kWh	57922	57922
Per cycle	kWh	234,5	156,5
Required in barge volume 1000	m3 particles	810	540
Energy	mWh	230	249
Including safety factor (50%)	mWh	346	373
Power needed in use	kW	467	336

Mixture density: $\rho_m = \rho_s C_v + \rho_f (1 - C_v)$

In-situ concentration: $C_{v,situ} = \frac{\rho_m - \rho_f}{\rho_{situ} - \rho_f}$

Haaland eq, friction factor: $f = \frac{1.325}{\left(\ln\left[\frac{e}{D \cdot 3.7} + \frac{5.74}{Re^{0.9}}\right]\right)^2}$

Mixture velocity: $v_m = v_s \cdot C_v + v_f \cdot (1 - C_v)$

Production: $Q_s = A \cdot v_m \cdot C_v \cdot F_t$

Situ production: $Q_{situ} = A \cdot v_m \cdot C_{v,situ} \cdot F_t$

$$\Delta P = \lambda * \frac{L}{d} * \frac{1}{2} \rho v^2$$

$$V_{crit} = 1.7\left(5 - \frac{1}{\sqrt{d_{mf}}}\right)\sqrt{D}\left(\frac{C_{vd}}{C_{vd} + 0.1}\right)^{\frac{1}{6}}\sqrt{\frac{S_s - 1}{1.65}} \qquad (4.19)$$

In Eq. 4.19 the particle diameter d_{mf} is in millimetres and the pipe diameter D in meters.

The correlation has an advantage of being based on data including those from various dredging pipelines. MTI recommends the correlation for grains of sand and gravel size and pipelines larger than 200 mm.

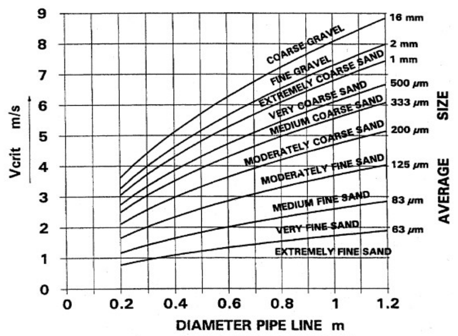

Figure 4.6. Critical velocity according to the MTI model (Eq. 4.19). The nomograph

Figure C.1: Adjusted spreadsheet for crawler energy and power calculation

D
Scenario Overview

This series of pictures provides an overview of the animations made in the clarification process of this concept. They are made using canva.com and the complete sequences are available on youtube. They can be watched by Clicking here.

Figure D.1: Barges cycle 1/6

Figure D.2: Barges cycle 2/6

Figure D.3: Barges cycle 3/6

Figure D.4: Barges cycle 4/6

Figure D.5: Barges cycle 5/6

Figure D.6: Barges cycle 6/6

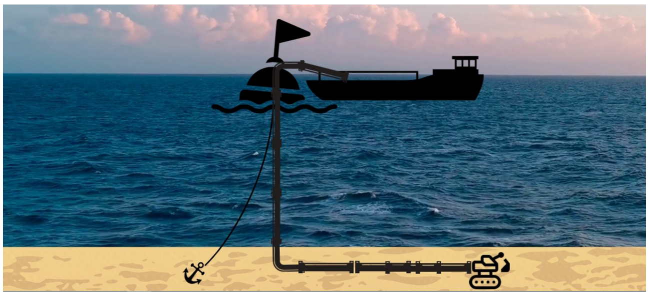

Figure D.7: Crawler cycle: filling barge in 3.1 hours 1/2

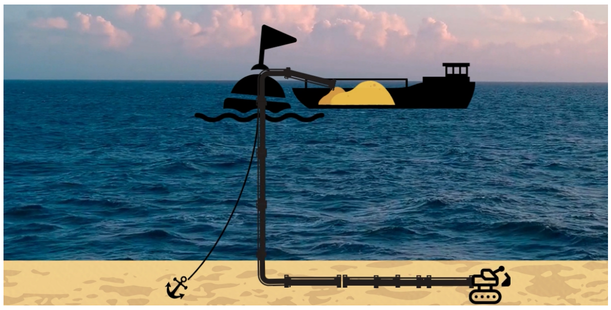

Figure D.8: Crawler cycle: filling barge in 3.1 hours 2/2