EMISSION FREE MAINTENANCE DREDGING

in a harbour environment

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Emission free maintenance dredging in a harbour environment

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Abstract

On request of Royal Boskalis Westminster N.V. a comprehensive research was performed regarding emission free maintenance dredging in a harbour environment. The project site is the Maasmond at the port of Rotterdam. It covers an area of almost 10 km^2 and, on average, a monthly volume of 400.000 cubic meters of sediment needs to be dredged. The operations are currently performed using trailing suction hopper dredgers (TSHD). Several new fully working emission free concept work methods were designed. These were assessed using a multi-criteria analysis, where emphasis was placed on energy reduction, reliability, interference, risk and safety. Given the scope of this research, costs are not decisive. General conclusions for the solutions contain the splitting of the total process. As the energy consumption of a conventional hopper is too high to operate on a battery cell, the work method is split into three different processes being: (i) gathering, (ii) pumping and (iii) transportation. Two work methods scored best in this research, Sloped Water Injection Dredging (SWID) and the Fully Autonomous Submerged Dredger (FASD). SWID consists of Water Injection Dredging vessels, fixed structures and autonomous barges. FASD contains the design of a submerged dredging vessel. It can be concluded that a harbour environment is suitable to perform emissions free maintenance dredging with only small alterations to the current technology.

Foreword

Before you lies the work of four friends and master students at TU Delft that have worked with great pleasure and joy on this multidisciplinary project. This project was performed over a time period of ten weeks in the third quarter of academic year 2020/2021. Prior knowledge about dredging stagnated after the introduction to dredging engineering course for two students. The other two students came in green as grass. After getting up to speed and a little "learning as you go", we were able to generate satisfying results for the client.

This report can be seen as the extension of the Memo that has been shared with Boskalis and TU Delft. The memo provides an overview of the results and takeaways from this research regarding emission free maintenance dredging in a harbour environment. This report will present the followed design process and more in depth calculations.

There are a number of people without whom this report would have never existed. First of all we would like to thank our supervisors from Boskalis: Sebastian Henrion and Hilbrand Druiven. We really enjoyed the weekly meetings we had and we are thankful for the provided opportunity. You taught us a lot on how to approach such ambitious problems. Still, we couldn't have done it without your guidance and provided hands on dredging experience. We would also very much like to thank our TU Delft supervisors Cees van Rhee and Martine Rutten for asking the right questions at the right time pushing us in the right direction, adding knowledge and for being always willing to take a meeting to answer our questions. Finally we would like to thank those who were so friendly to take a meeting with us and share their expertise on water injection dredging, pipelines, ship-building or other dredging related fields of interest. These are: Ronald Rutgers (PRISMA), Erwin ten Brummelhuis (MSc Thesis on WID, TU Delft), Jan Westhoeve (Royal IHC), Bas Nieuwboer (Royal IHC) and Thijs Schouten (PhD candidate, TU Delft).

Pieter, Fabio, Jan and Floris

Contents

1 Introduction

On March 23 in 2021, the Ever Given, a container vessel of 400 meters, got stuck in the Suez Canal and prohibited more than hundreds of ships to pass. After it had been stuck for more than week, Boskalis used a combination of dredging methods and tugboats to free the ship from her position. The Suez Canal is a highly dense traffic area and the blockage caused major logistical problems with big financial consequences. One thing is sure, avoidable accidents like this should be prevented at all times.

One could argue that the width of the canal imposed a certain risk of such an event. The canal could have been widened to make sure that the longest ships are not able to block it completely when lying perpendicular to the canal. It can be concluded that some measures could have been taken to prevent such a hick-up.

The accessibility of areas with large amount of marine traffic, like the Suez Canal, cannot be underestimated and must be assured under all conditions. Another example of an area where accessibility is of great importance, is the harbour of Rotterdam.

In 2019 Boskalis was granted the contract to perform maintenance dredging at the Maasmond in the harbour of Rotterdam (Boskalis, 2019). The harbour is notorious for the large amount of traffic, and therefore a reliable and accessible entrance must be assured. During the last century, the depth of crude carriers and container vessels increased up to 25 meters. The risk of ships stalling on the river bottom and causing delays must be avoided at all times. Boskalis is responsible to maintain an accessible entrance to the harbour area of Rotterdam. To ensure an accessible entrance, continuous maintenance has to be performed. The depth of the Maasmond slowly decreases over time due to in flowing sediment from the North Sea and the Dutch rivers.

The aim of Boskalis is to be carbon-neutral in 2050. To reach their goals, the R&D department is granted a far-reaching but essential task. They plan to develop new work methods to cleanse the dredging industry, which is infamous for its polluting vessels. The current amount of diesel that is used to operate Boskalis' fleet is the biggest hurdle in reaching their goals.

This project aims to improve the sustainability of the maintenance that is performed on a daily basis at the Maasmond. Currently, polluting hopper dredgers are being used to perform this exercise. The goal of this project is to develop new emission free work methods to perform the maintenance in the port of Rotterdam. These work methods have been assessed using a multi criteria analysis. The conclusion contains a recommendation for Boskalis on how to continue their operations in Rotterdam.

The report is build up in a structured way such that it follows closely the chronological steps of this project. In chapters 2 and 3, the problem definition, the research question and the methodology are stated. In chapter 4, 5 and 6 the new concept work methods are elaborated. The MCA is run in chapter 7. Possible alterations to some newly elaborated work method are shown in chapter 8. Finally the conclusion and recommendations for further research are displayed in chapters 9 and 10.

Boskalis

2 Problem description

The current maintenance dredging at the Maasmond is performed using a conventional hopper dredger: The Strandway, figure 1. A hopper dredger like the Strandway, is what Boskalis likes to say, an all-trick pony. It is a very reliable vessel to perform maintenance dredging. However, if Boskalis wants to meet their ambitious goal of being carbon-neutral in 2050, vessels like the Strandway cannot be used anymore to perform operations like maintenance dredging. The fuel consumption of this hopper is quite impressive. The operation in the Maasmond implies that for each liter of diesel consumed three cubic meters of sediments are removed. When taking into account that an annual average of 4.8 million cubic meters needs to be removed to ensure an accessible harbour, roughly 1.6 million liters of diesel is consumed doing so. This diesel produces a total amount of 4300 tons of CO2. To meet Boskalis' goals, this number needs to be drastically decreased.

Additionally, the hoppers often have to come from distant places. Valuable time and a significant amount of fuel are being spent traveling from and to Rotterdam harbor.

Figure 1: Boskalis' Strandway

Ambitious Goals
This project is going to investigate the possibility of removing emission out of the equation of maintenance dredging. Therefore, the ambitious research question for this project is:

*"Design a cost efficient, **emission free** concept work method for maintenance dredging works in a harbour environment for a recurring yearly cycle."*

Emission free is written bold, because it is the main target of this project. The location for the maintenance is the Maasmond and the Maasgeul compartments, see figure 2. The size of the area equals approximately $10km^2$. On average, somewhere around 400.000 cubic meters of sediment need to be removed on a monthly basis. An interesting part about the site is that the sediment is not spread equally over the entire area. The Maasgeul 0-6 area contains about 50% of the all the sediment and primarily consists of sand particles. The inflow of sand in this area originates from the North Sea. The RT MAMO E area is responsible for almost 40% of the sediment and primarily consists of clay particles which originate from the Dutch river system. Finally, the RT MAMO F area, located in between the other compartments, is an area comparable in size to RT MAMO E but only contains 10% of the total sediment.

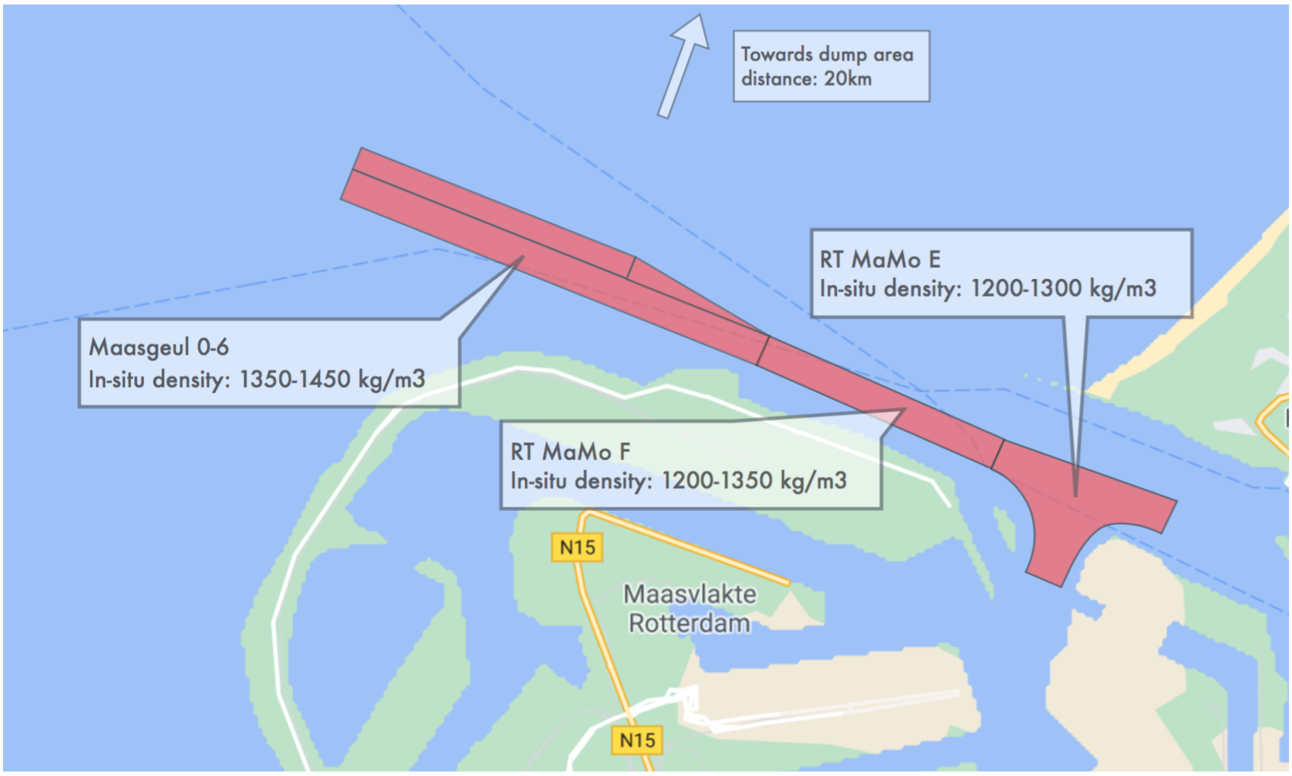


Figure 2: Maintenance Area: Maasgeul and Maasmond

Project Boundaries

The objective of this project is to write a recommendation for Boskalis on how to adjust their work methods to reach their targets without polluting the environment with toxic exhausts. The mission to reduce all emissions from the maintenance operation is an ambitious one. To withdraw the creative process from certain limits, inevitable financial boundaries are left out of the equation. Additionally, the technological obstacles should not disqualify new ideas. The technology readiness level will be assessed, but is not decisive, because the realisation of the final work method might be realised 20-30 years from now. Furthermore, the application of sand bypasses, or any other technique like current deflecting walls to prevent sediments to settle in the harbor area is not taken into account in this project as the main scope of this research is to address and look into alternative ways to make the current dredging work method emission free.

3 Methodology

This chapter will describe the method used on finding the solution for the research question. First the overall approach is addressed, then the main categories on which each concept work method is analysed will be introduced, next the proposed design process is shown.

3.1 Overall approach

As will be shown in chapter 4, a conventional TSHD is not able to run on a sustainable energy carrier as the hopper requires too much energy to complete the entire cycle of dredging, transporting and discharging. The energy-density of the sustainable energy carriers is simply too low. To obtain a good new emission free concept work method for the problem we will approach the problem keeping the following three incentives:

- **Improve the efficiency of the process**, by making the process more efficient so that less energy per cubic meter of sediment is needed. By doing so, the use of a sustainable energy carrier could be enabled.
- **Use a continuous process**, so that the required dredging discharge is lower. Therefore, the required installed power for e.g. pumps can be also be lowered. This way the energy demand over time unit is lower and this enables the use of a less energy dense (green) energy carrier.
- **Split up the entire process into sub-processes**, by dividing the process into smaller parts, the required installed power can be decreased. These sub-processes can work simultaneously, but can also alternate each other and are stated below. It also brings the advantage that each process can be optimized for its purpose (task-specific).

Elaborating on the last point, every concept design needs to fulfil the three tasks below whilst using nothing but green energy. This was always the starting point when designing a new concept. Some concepts however will combine tasks.

1. **Collection of the sediment**, gathering all the sediment to a central place enables the use of a fixed structure for pumping, this way the power needed to suck the sediment to sea level does not have to be installed on the dredging device. This for instance reduces the dredging devices size. Besides that, the fixed structure can be connected directly to the grid, avoiding a - often costly or bulky - sustainable energy carrier.
2. **Excavation**, once the sediment is gathered to a central location it needs to be pumped into the transportation device. As already stated before, this pump can now be a fixed structure. The installed power can be minimized as it can work continuously.
3. **Transporting of the sediment to the fixed dump area**, finally the sediment needs to be transported from the Port of Rotterdam to the designed dump area, where it is then released.

3.2 Design process

For the design process the double diamond approach is used. This is visualized in figure 3. The process starts with the problem as described in chapter 2. Next, research is performed such that the consultants are all aware of the new and state of the art techniques of the dredging and shipping industry. By doing so, insight is gained regarding to what is preventing the dredging industry from going emission free.

To come up with a great variety of concepts, the earlier research regarding different dredging methods, alternative fuels, pipe systems, pumping, sediment behaviour and transportation is used. The main intention is to come up with a **new** concept work method. This means that we are looking further than just alternative fuels alone, nevertheless these will be assessed in chapter 4.

With this in mind, multiple concept work methods are designed and will be presented in this report. These concepts are put to the test in the form of a multi criteria analysis, MCA, to see how the concept work methods compare to each other and to identify strong points and weaknesses. Later on, iterations for some of the concepts and combinations of concepts are also proposed.

The ultimate goal is to present the client an overview of the possibilities regarding emission free maintenance dredging alongside of advising what are the best solutions.

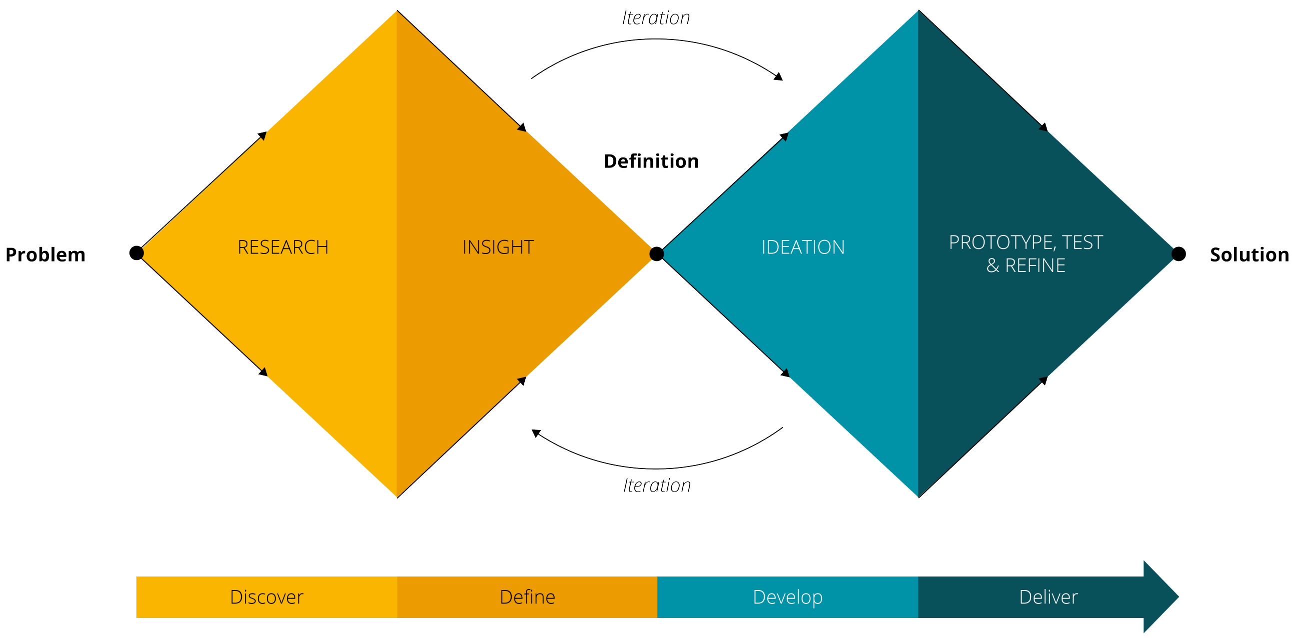


Figure 3: Visualization of the double diamond approach. Source: (NoHitch, 2019)

3.3 Main categories of MCA

The new concepts are to meet certain standards, of course all concepts need to be able to complete the yearly dredging maintenance, but they also have to be zero emission. The four main categories, that are worked out further in chapter 7, on which the concepts are analysed and rated on are:

1. **Carbon footprint & sustainability**, each concept needs be zero emission during its operation. Still, some concepts will require less energy during operation than others. Besides this, some concepts require more material, or other kind of vessels for the construction that are not zero emission. Therefore we will also consider the amount of material and the difficulty to implement the concept work method.

2. **Reliability**, as the working environment of dredging devices is harsh, the work method needs to be robust and reliable such that the amount of maintenance remains limited over time.

3. **Interference, risk & safety**, the entrance of the Port of Rotterdam needs to be ensured. Incoming and outgoing traffic can not be hindered by the concept work method. Risk and safety of the operation is also considered and needs to be minimized.

4. **Cost**, the costs of a project like this will almost always be the decisive factor for the executive company. If the project is not viable then it will not be realised. In this case the main goal is to be zero emission and not financially optimal. In this report, cost is taken into consideration, but only up to a certain extent.

In chapter 7 the multi criteria analysis will be performed, the criteria for the analysis are all based on these four main categories. When designing new concept work methods these categories are always taken into account.

4 Alternative Fuels

In order to get to an emission free concept work method, the energy supply needs to have a net zero emission, this can be achieved by emitting zero emission or through a carbon dioxide capture process that is emitted during the combustion. For the former the concept work method should in the end be running on energy from a green energy source such as wind, tidal or solar. This energy can either be directly delivered to the work method via the electricity grid or can be stored in an energy carrier. Of the latter we will consider the three often mentioned possibilities: hydrogen, methanol and batteries. The final stage will be addressing the great amount of residual energy streams that are present in the Port of Rotterdam. The goal of this chapter is to provide a good overview of the possibilities of green energy carriers.

4.1 Hydrogen

The port of Rotterdam aims to become the worlds largest *green* hydrogen hub (Weterings, Randolf, 2020). This means that hydrogen will be widely available at the project-site. Hydrogen is made by the electrolysis of water. When renewable energy is used for this, hydrogen is a clean energy carrier. When it is used, hydrogen can be converted back to electricity in a hydrogen cell. The energy efficiency of hydrogen production lies between 70% and 80%, which is relatively high. Liquid hydrogen has an energy density of 8 - 10 MJ/ℓ (Chi & Yu, 2018) (Mazloomi & Gomes, 2012). This is low compared to other fuels. Liquid hydrogen can only be kept at very high pressures, posing more complexity. The majority (95%) of hydrogen is still being produced from fossil fuels, therefore it is important to make sure that hydrogen comes from a green source.

Another problem with hydrogen is the fact that the tanks can not be filled and emptied completely. As you would fill up the tank the pressure increases and with that the temperature. For this reason it is found that the hydrogen tank can only be filled up to 70%. As hydrogen must be kept at $-250°$C the isolation layer around the tank is very big and also very expensive. All together only 60% of the tank is used for storage when using hydrogen.

4.2 Methanol

The use of methanol as green energy in a "methanol economy" carrier was suggested by Nobel Prize winner Olah (2005). The benefit is that it has a relatively high energy volumetric density of 15 MJ/ℓ (19.7 MJ/kg) and can be used as combustion fuel, preferably in a methanol idealized engine. Furthermore, it is liquid under atmospheric conditions, making it easy to transport. In order to be green, methanol should be created from captured carbon dioxide. This carbon can be extracted from industry sources (probably available in the port of Rotterdam) or straight out of the atmosphere (making it emission neutral). Less preferable would be to capture the required carbon from biomass. The production of methanol also requires hydrogen, energy and a number of catalysts. The energy efficiency for the creation of methanol lies at about 50% (Bos, Kersten, & Brilman, 2020). Bos et al. Estimated costs for production of green methanol to be 800 euro per ton (including wind turbine capital cost), hydrogen electrolysis being the main cost driver. It seems that the technology for this technique is available, however in Europe, methanol is not yet used as much as batteries and hydrogen are. China offers a methanol gasoline mixture (85 - 15% respectively) at gas stops since 2007 (Kemsley, 2007).

4.3 Lithium-ion battery

Lithium-ion batteries are a broadly used green energy carrier. From small energy consuming devices up to electric vehicles and storage power stations. The lithium-ion battery is the type of battery with the highest energy density of all the battery types, with a density of 1.8 MJ/ℓ. This is fairly low with respect to methanol and hydrogen, but batteries are easy to implement into devices. One can design the battery-pack to fit the required space and when placed the "energy" is not in liquid or gaseous form, so it is static. This gives batteries a great advantages over hydrogen and methanol.

A problem with batteries is the ageing and degradation of the cells, causing a needed replacement after a period of time. This of course can be minimized by charging in low temperatures and operating in steady room temperature, but is unwanted. In addition to that, the charging time is higher compared to the filling time of other energy carriers.

The investigation and development in solid state battery technology could prevent a great part of these disadvantages (Vandervell, 2018). It is expected that the energy density will triple (N. Dudney, 2015). Charging-time will drastically reduce and reduction in ageing of the battery is also feasible. It seems that the availability of solid state batteries will be a huge game-changer in the field of sustainable energy carriers.

4.4 Residual energy streams

The harbour environment contains a great amount of residual energy streams. For instance, the high number of factories produce bulks of heat which can be used for other purposes like producing hydrogen, methanol or charging batteries. This is the start of an integrated energy system, which also improves the use of renewable energy as they can be used at places that need the most energy (SmartPort, 2020). As the Port of Rotterdam is also investing in becoming the largest green hydrogen hub in the world the investigation in available residual energy streams in the port aligns with this vision. Models that predict the weather can give insights in the division of the green energy supply. Some factories use a bit less, where other use a bit more. When an oversupply of energy comes from the renewable source this can be used to create hydrogen. Adding the smart integrated energy system where residual energy streams are used for other operations or directed to the hydrogen storage, a great reduction of CO_2-emission can be achieved. Fixed structures or charging stations used in the dredging process can be connected to the smart energy grid. When a hydrogen energy carrier is used it can be filled from the energy storage. An integrated smart energy system is therefore a big, but good investment possibility.

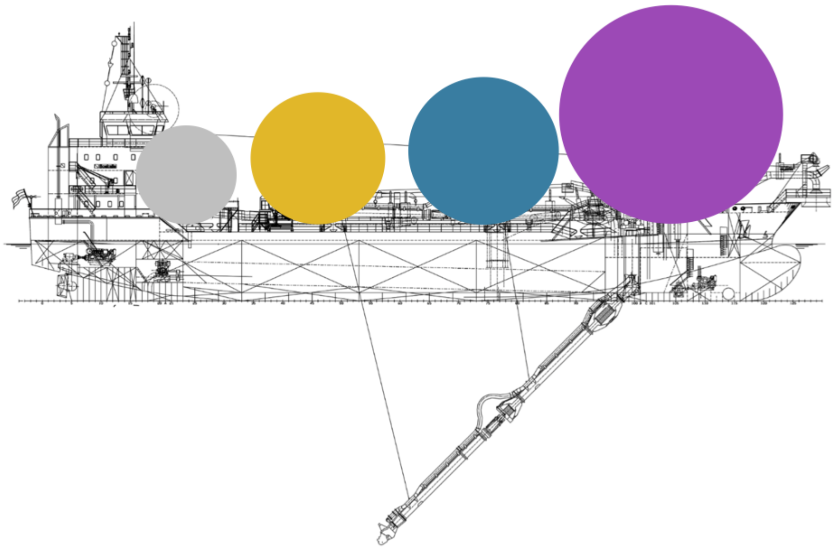


Figure 4: Visualization of required volume per fuel. Grey: diesel, yellow: methanol, blue: hydrogen, purple: lithium-ion batteries

The aim of this chapter is to give useful insights in the available green energy carriers that could possibly be applied in all the concepts. But it will also show that the conventional way of dredging is not suitable when trying to directly swap the alternative fuels for the used diesel. As a benchmark we take a look at the Strandway, a TSHD from Boskalis with a total installed power of 9472 kW. It is known that the Strandway has a fuel capacity of $380m^3$ of diesel, with the energy densities of diesel, being 40 MJ$/m^3$, and the densities of the other energy carriers the size of the tanks of the other fuel carriers can be calculated. If the tanks were purely spherical the sizes compared to the Strandway are shown in figure 4. These sizes do not include the tanks itself, they only show the volume of the energy carrier required.

5 Transportation and pumping

In chapter 3 it is explained how the conventional work method will be split up into smaller sub-process. Each sub-process can then be designed in a task specific manner. In this chapter the current method of transporting the sediment to the dump area is addressed, followed by recommended specific solution to the transportation. Later the pumping via a fixed structure will be elaborated.

5.1 Transportation

The current maintenance dredging is performed by conventional trailing suction hopper dredgers. This vessel pumps the sediment into its basin and sails to the dump area to discharge the load. The idea to split this vessel into separate parts will bring some advantages. A barge with the sole purpose of displacing sediment from and to the dumpsite can be designed task specific. The shape of this barge can be adjusted to optimise parameters like the volume of the cargo, drag coefficients and power demand for propulsion. Conventional spilt barges are already part of the Boskalis' fleet. Ships like the Wadden 1-4 have been taken as the inspiration for the new designs, depicted in figure 5.

Figure 5: Split barge Wadden 4

5.1.1 Energy demand conventional split barge

The Wadden 1-4 is equipped with a propulsion system with a total installed power of 1074kW, a carrying capacity of 935m^3 and has an average cruising speed of 6.8 knots, which equals to 3.5m/s. The distance to the dumpsite is about 20km. Assuming the engine runs on 75% of the total capacity, the time required to sail from and to the dumpsite is about 2.5 hours. The total energy of one trip would add up to 6.9GJ. Divided over the amount of cubic meters of sediment, the total energy per cubic meter is estimated at 7.3 MJ/m^3. The energy that would be used to perform the transportation with a conventional split barge is known from this point. A ship like the Wadden 1-4 would require almost 200 liters of diesel to sail from and to the dumpsite. In the aim of achieving the goal of this research, performing maintenance with zero emissions, this needs to be reduced.

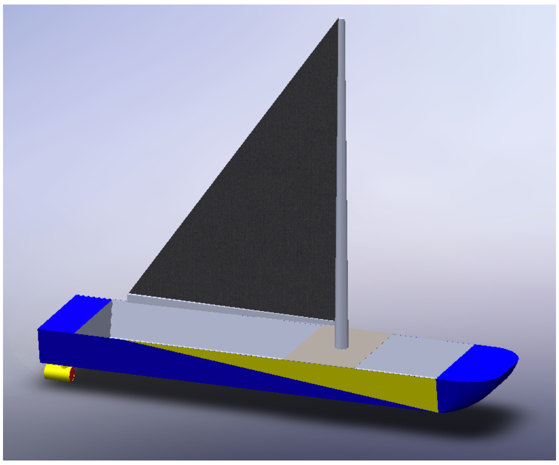
The conventional split barge could be equipped with a lithium-ion battery pack. For one ride, it would require a battery pack $200\text{L} * 40/1.8 = 4444\text{L} = 4.4m^3$. Where 40 and 1.8 are the energy densities in MJ/ℓ for diesel and li-ion batteries respectively. The battery pack needs to be large enough to supply energy for a couple of cycles before it needs to recharge. If the battery is large enough for 8 rides and a little reserve, the size of the battery pack will more or less the size of a 20ft container. The weight of the battery can be neglected in comparison to the weight of the sediment that is transported by these vessels.

To increase the efficiency to perform the transport to and from the dump area, new vessels have been designed. The new vessels aims to reduce the energy required for the transport. When the energy consumption decreases, the size of the battery-pack can be reduced. From the thee proposed designs, two designs make use of wind energy for propulsion and one uses solar energy.

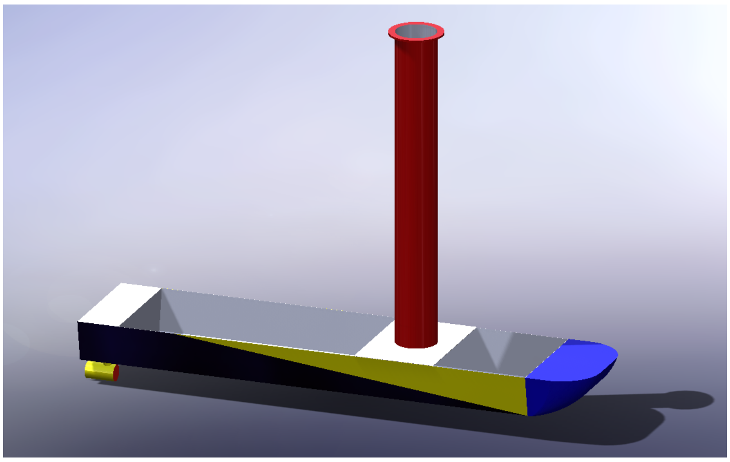
5.1.2 Autonomous barge: conventional sail

Design 'AB-S' is a new type of split barge improved with mast and sails. Wind energy is widely available in Dutch coastal areas. To meet the goals of the project, this free energy must be used as much as reasonably possible. The cruising speed of AB-S will be slower than its conventional counterpart and it also might not always be possible to sail in a straight line to the destination. These are the sacrifices that come with this (emission) free energy. Wallenius Marine, Swedish research institute SSPA and the Royal Institute of Technology in Stockholm are working on a freight carrying vessel which potentially reduces energy usage with 90%, taking 50% more time than normal vessels to cross the Atlantic (Oceanbird, 2020).

In addition to the sails, the AB-S will be equipped with 2 azimuth thrusters that are electrically driven by a battery-pack or a hydrogen fuel tank. These thrusters will ensure safe maneuverability when the ship is positioned when it is loading and unloading. The installed power of these azimuth thrusters will have a similar installed power to the thrusters on the Wadden 1-4. The total required fuel for the operation of the AB-S will be marginal in comparison to the Wadden 1-4. A design visualization of the AB-S is displayed in figure 6a.



(a) Conventional sail



(b) Flattner rotor sail

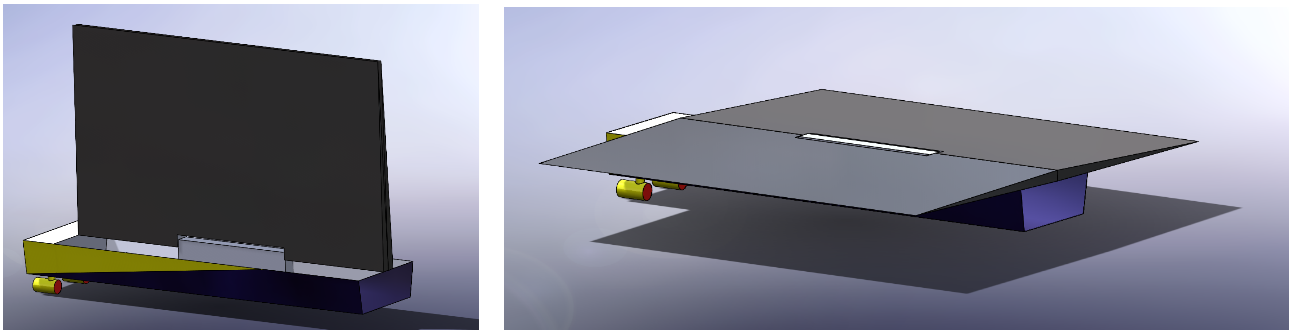
Figure 6: Design visualization for sailing autonomous barges.

5.1.3 Autonomous barge: Flettner rotor sails

The second design of the transport barges is design 'AB-F'. This design benefits of the wind energy using Flettner Rotors. Even though this technology has been developed in the twenties of last century, this technology has not been used widely in the industry. Reduction of fuel with use of Flettner Rotors for conventional cargo vessels can lead up to 25% reduction in fuel under favorable conditions (Network, 2021). Yearly averages were shown to be around 8.2% (News, 2019). The AB-F is also equipped with the azimuth thrusters. The energy carrier needs to have a larger capacity than the AB-S design because energy reduction is less. Further energy reduction by using the Flettner Rotors still need to be researched. The possibility of the ship sailing purely on the forces of the Rotors can only become feasible a very high wind speeds (Architects, 2015). The AB-F design is displayed in figure 7.

5.1.4 Autonomous barge: solar panels

The third design for of the barge depends on solar energy to harvest energy for propulsion. Even though the Netherlands is not known for being a sunny country, during the months between April and October sun is available. The energy required to propel a vessel at slow speeds cannot totally depend on solar panels. However, a reduction in required power is possible when making use of this solution. Vattenfall advertises with solar panels that are able to generate 630 MJ/m^2 per year.
In return, this vessel can be used in other places over the world in the other half of the year. The design is displayed in figure 6a. The idea is that this vessel is able to withdraw the solar panels when sailing in the harbour. When the vessel is sailing in open sea. It will be able to open up the solar cells and capture energy from the sun to power the engines.



(a) Closed configuration during loading

(b) Open configuration during charging

Figure 7: Design visualization autonomous barge with solar panels.

The solutions for the barges can be combined as well. The barges can be mounted with sails in the winter, when the wind is blowing most powerful. In the summer, the sails can be removed of the barge and the solar cells can be mounted. This way, it is possible to make as much use of the free energy as possible. These new designs will help to reach the goals to decrease emission during operation to zero.

5.1.5 Autonomy of barges

Split barges are simple devices that most of the time do not require “on deck” actions when performing the transport of the sediment to the dump area and sailing back. With the technology of today it is possible to design these ships in such a way that they are remotely controlled from a shore control center (SCC). Autonomy will bring some advantages for these ships. The use of space can be optimized for carrying more cargo. Additionally, the new designs have a cruising speed which is much slower than the conventional split barges. Therefore the crew on these ships will be nonessential, expensive and a waste of time. The necessary maintenance can be performed in times when wind speeds are low and production is suspended.

5.2 Pumping

Once the sediments are gathered at the prescribed location (collection process - different for each concept work method), the second step of the process begins. This step consists in pumping or lifting the sediments from the seafloor to the transportation vessel, making use of an hydraulic pump called the *Punaise* pump.

This dredging device has already been used during the '90s, and it was proved to be a solid technology in pumping mud and sand materials from the seafloor. The pump itself is a remotely operated, water tight submerged dredge that resides on the seafloor, pumps sediment without impact to navigation, and is not affected by storms. Because it is located on the seafloor, it is very tolerant of adverse surface wave action. (Visser & Williams, 1997)
The Punaise is connected to the shore station by a flexible pipe, which has a dual function of powering and discharging the slurry. All processes are fully automated, except diving and floating, so that the entire pumping process can be controlled from the shore by just one person, which makes the labor costs relatively low.

5.2.1 Operational working principle

As material is removed from the bottom, a pit is generated and the Punaise is located at the lowest point. The submerged pump excavates by hydraulic erosion. It creates an unstable slope upon which sediment flows to the suction intake. As the dredging continues the pit grows in size until the desired depth of 25m is reached. It is possible to move the device when the pit is considered deep enough, but is also possible to dump or plough new sand to the pit and hence on top of the Punaise so that it can keep dredging without any interruption or need to move it somewhere else. Almost all of the later presented concepts make use of this method.

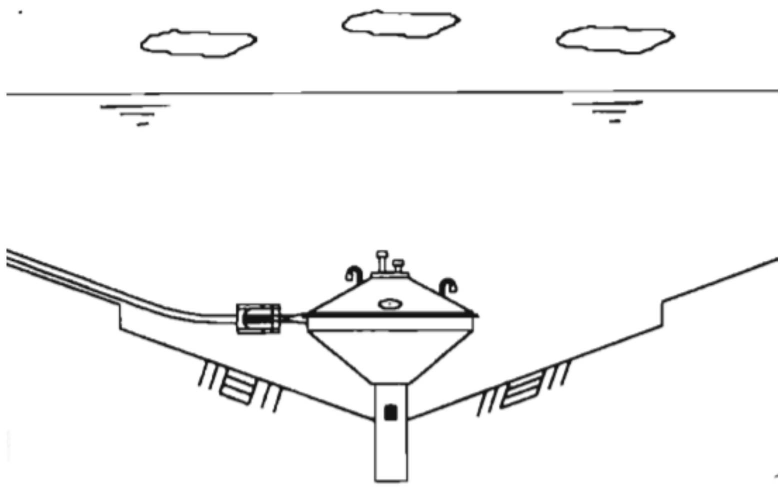


Figure 8: Punaise suction. (Visser & Bruun, 1998)

5.2.2 Energy consumption

Two Punaise pumps that have already been designed namely the PN250 and PN400, are used here as a reference for this project. The pump capacity as well as the energy requirement are recalculated in order to be able to meet the target amount of sediments that have to be dredged inside the Maasmond area.
The total electrical power supplied from the on shore station to the PN250 was 1200kW and the pump had a nominal flow capacity of 800 m^3/h (Visser & Williams, 1997), therefore the standard discharge rate is calculated to be 0.22 m^3/s. This leads to an overall energy consumption of:

$$E_{pump} = \frac{1200kW}{0.22m^3/s} = 5400kJ/m^3 = 5.4MJ/m^3 \tag{1}$$

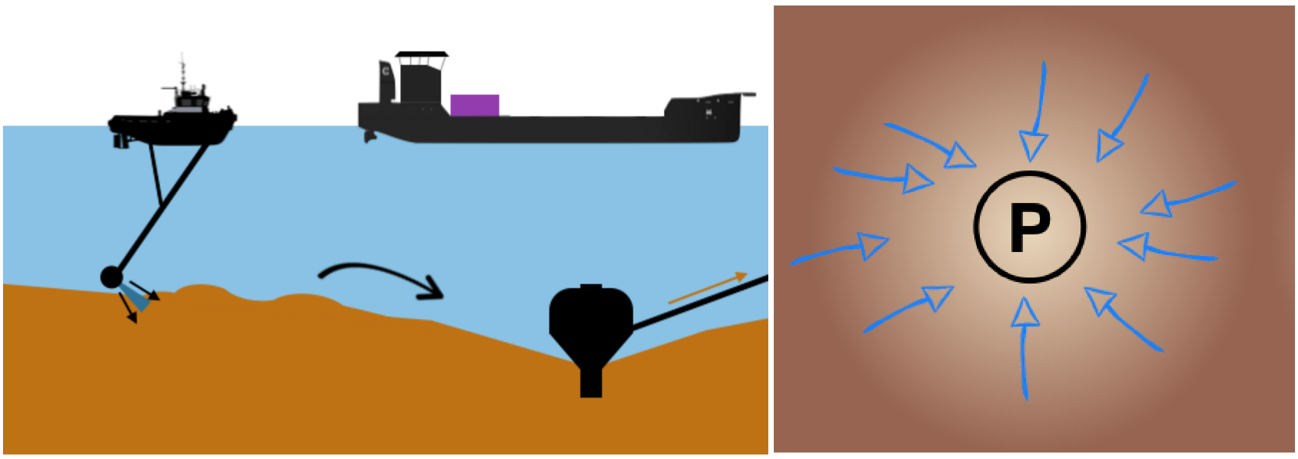
The starting point is the assumption of a linear relation between the pump capacity and the energy required, then the flow rate is adjusted and recalculated accordingly for each work method considered, but the energy consumption per cubic meter will remain constant as the power linearly increases/decreases with the flow rate. The estimated energy consumption of $5.4MJ/m^3$ is therefore taken as a reference for every work method.

6 Concept work methods

This chapters shows the results of the initial full concepts ideas, these were generated while considering the incentives introduced in chapter 3. Some of the concepts make use of pumping and transportation devices shown in chapter 5. These concepts will later on be tested with the multi criteria analysis in chapter 7.

6.1 Sloped water injection dredging (SWID)

This method uses water injection dredging in combination with a sloped bed to collect the sediment in a central location. At this central location a fixed pump is placed. Water injection dredging brings settled sediment back into suspension by injecting it with water under high pressure. The suspended sediment causes the water to have a higher density and as heavier fluids tend to get below lighter fluids, the suspension will start to 'travel' downhill to the lowest point, this is depicted in figure 9. Currents located at the dredging site can interfere with the density current, but can also help the sediment travel to the lowest point, the sediment trap. A permanent pump is placed in the sediment trap. This fixed structure will pump the sediment up to the surface, keeping the sediment trap the lowest point. This way the sediment will travel towards the pump by itself.



(a) Side view (b) Top view

Figure 9: Top and side view of the SWID concept work method

6.1.1 Advantages

According to IADC (2013), water injection dredging has many advantages. The most important advantage is that it requires less energy than a conventional TSHD. The SWID only injects water and the sediment is transported horizontally over a slope instead of vertically though a suction head. On top of that WID vessels are smaller in size, are more maneuverable and require less crew. A case-study, on which later more, by Kirichek and Rutgers (2019) showed that cost reductions can add up to 40%.

PRISMA (PRogramma Innovatie Sediment MAnagement), a division within the Port of Rotterdam, is also researching this dredging technique. PRISMA is looking into more sustainable ways to perform maintenance dredging in the port. One option is to measure the "real" depth in the waters of the port. At the moment, the bottom of the river is considered to be the spot where the density of the water-soil mixture becomes 1200 kg/m^3. However, large ships with a higher draft than the measures depth in this case, can still sail through this. PRISMA researches methods to find the "real" depth. Putting the sediment into suspension and using PRISMA's new "real" depth, would result in a lower dredging frequency.

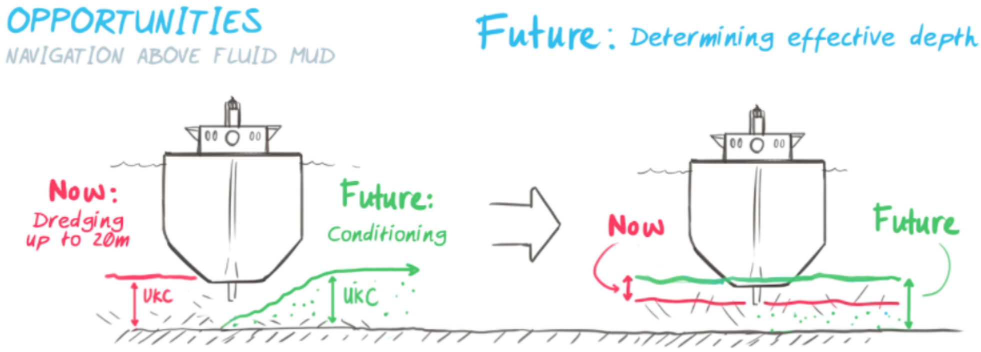


Figure 10: The effective depth. Source: PRISMA

This concept is easily applicable elsewhere in other harbors for regular maintenance works making this concept quite flexible to adjustments depending on the amount of the sediments and shape and size of the area that needs maintenance. However, water column depth in this case needs to be taken into account and the beam length has to be adjusted accordingly.

6.1.2 Detailed Work Method

When performing water injection dredging it is difficult to accurately keep track of the suspended sediment. The sediment density current is influenced by many factors like tidal currents and currents generated by shipping. To show WID's effectiveness this section will display a test study performed by Kirichek and Rutgers (2019) in the Calandkanaal. This is a canal close to the project site in the harbour of Rotterdam.

Case Study

The research in this section was performed by PRISMA. After some investigation using flow models, the Calandkanaal was determined suitable for a WID field test. A box shaped sediment trap of 80.000m^3 was created using a TSHD. An area of 0.8 km^2 was water injected using the JetSed, a WID vessel of Van Oord. According to Kirichek and Rutgers (2019) the injection of water took almost 90 hours. The JetSed has an installed power of 1621 kW. Assuming full power, arguably, a 90 hour job results in a energy consumption of 500.000 MJ. This was used to inject the bottom of the river to fill the sediment trap once. This resulted in an energy usage of 6.3 MJ/m^3 for gathering the sediment. This number is not showing a great improvement of efficiency compared to the original hopper dredger. However, the researchers made two important annotations: [..."After the WID action, no maintenance dredging was needed in the pilot area for more than two months. In this area, on average, every month maintenance dredging is required"...] (Kirichek & Rutgers, 2019). The conclusion can be drawn that either after the sediment trap was filled, the sediment ended up somewhere outside the test area or that the suspended sediment has prevented other sediment to flow in from outside the test area. On top of that the researchers state that [..."Overall maintenance costs in this area where lowered with 30% - 50% compared to normal maintenance costs"...] (Kirichek & Rutgers, 2019). It is still unknown though where a large part the sediment actually ended up settling.

Operation at the project site

In the case study above, an area of 0.8km^2 was injected with water. For the project site of the Maasmond, an area of 10km^2, it is decided to use 10 sediment traps of each 40.000m^3. This way every sediment trap is responsible for an area of 1km^2. Following the case study, it would take one WID vessel approximately $90 \cdot 10 = 900$ hours, = 37.5 days to work the total area. To perform this amount of WID in one month, 30 days, two WID vessels would be required, each operating for 15 hours per day. Each of the fixed pumps has to deal with an average volume of $0.04 \cdot 1.000.000 = 40.000m^3/month$. This can be pumped out continuously ($56m^3/h$), keeping the sediment traps empty all the time. Another option would be to only empty the trap before WID starts, pumping with larger discharges. The right equilibrium has to be researched in more detail.

To show a possible configuration, it is chosen that 5 emission free barges will be used, each having a capacity of 1000m^3. The time it takes to transport the sediment to the dump area and sail back is a total of 3 hours. To add up to the total amount of sediment (avg. 400 000 m^3 per month), each of the 5 barges has to make 80 trips per month. This way, each of the barges is sailing 240 hours of the total 720 hours available in an average month. This way there are 480 hours left for filling, charging and possible required maintenance.

Again, it remains to be determined what would be the ideal configuration of autonomous barges together with efficiently using the permanent pumps in the sediment traps.

6.1.3 Remarks

- **The energy consumption** of WID was shown above and is calculated to be 6.3 MJ/m^3. On top of that there is the energy usage of the punaise pumps that use 5.4 MJ/m^3 (see section 5.2). As shown in section 5, energy consumption of transport is 7 MJ/m^3. Together these add up to 18.7 MJ/m^3. The WID consumption is however based on one case study, assuming full power and not taking into account the reduction in maintenance dredging in the following months. Energy consumption is therefore expected to be lower than 18.7 MJ/m^3.
  Van Oords JetSed has a weight of 237 ton, which is light for a dredging vessel. The emission during construction of that amount of steel is 450 ton CO_2.

- **The interference with traffic** is low as the sediment is transported to the sediment trap underwater requiring less sailing hours. Besides that, the WID vessel is relatively small, making it easy to maneuver.

- **Robustness** of SWID is high as long as the conditions of currents and bathemetry are suitable for SWID. The ship is relatively small and has not a lot of moving parts. The mechanism for water injecting it also relatively simple.

- **Costs** Hopper dredgers are sold for approximately 50 million euro. As water injection dredger vessels are smaller than hopper dredgers and the technique is less complicated, two WID vessels will add up to 25 million euros. On top of that there are the 10 punaise pumps, they are assumed at one million each adding another 10 million euro. Total CAPEX add up to 35 million euros. Regarding OPEX, WID vessels operate with less crew than the hopper dredger and use less energy. OPEX is therefore estimated at half of the hopper: 25.000 €/day.

6.2 The poolbuoy concept (PB)

This concept was developed by taking a pool cleaning robot as inspiration of the work method, depicted in figure 11. A suction head can move over the bottom of the harbour to collect the sediment. A flexible pipeline can be connected to the suction head to pump the sand to a central located gathering point.

Figure 11: Pool cleaning robot as inspiration for the design

An adjustment has been made with respect to the manoeuvrability of this robot. The rough and silty environment is not very suitable for a self propagating robot. For this reason the design has been altered to a suction head which is attached to a vessel that carries the suction head and sails on the surface of the river. This vessel is responsible for manoeuvring the suction head. The new design is displayed in figure 12. The red cylinder is the flexible tube that connects the suction head to a central pipeline system. The four grey cables are connected to the carrying vessel.

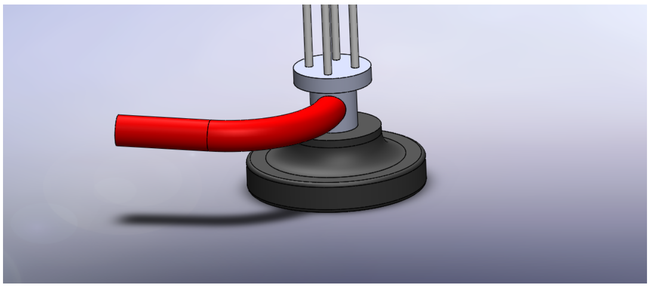
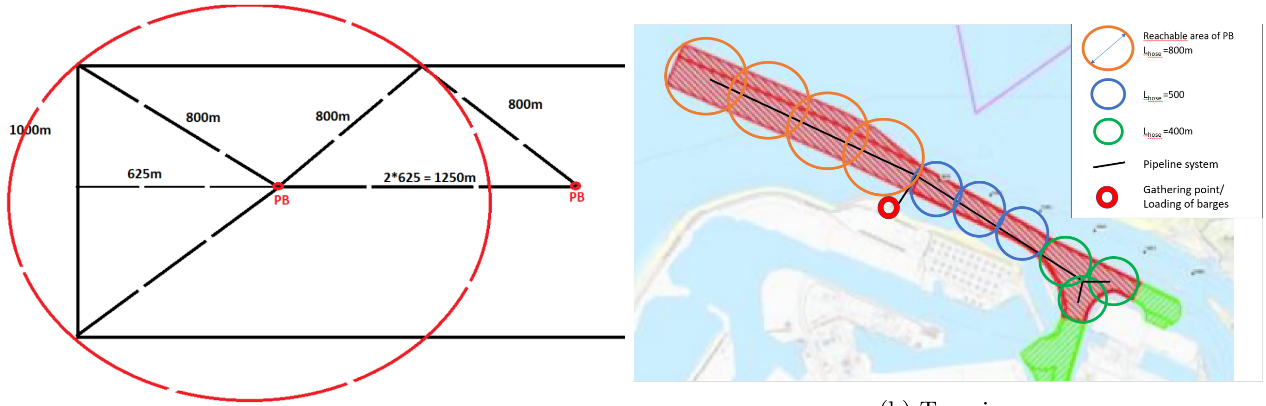


Figure 12: Poolbuoy design

The suction head is connected to a pipeline system through a flexible tube. The length of this tube is modified for the different areas. For example, in the Maasgeul 0-6 area, the tube has a length of $L = 800$m. The poolboys, PB's, can be placed on central points in the center of the Maasgeul so the entire area can be covered. The width of the end of Maasgeul 0-6 is about 1000m. The total area the can be covered by the PB is covered by the red circle as can be seen in figure 13a. When using this spacing, four PB's are able to cover the entire Maasgeul 0-6 area. Three smaller PB's can be used in the MAMO-F area, for the amount of sediment in that area is much less. In the area of MAMO-E, the amount of sediment is similar the the amount in Maasfeul 0-6. For this area has been chosen to use three PB's with a shorter flexible tube. The range of these PB's does not have to be that large as in the other areas. The total work area of the PB's is displayed in figure 13b.



(a) Side view

(b) Top view

Figure 13: Placement of the PB's

6.2.1 Advantages

The PoolBuoy system has advantages in three categories. Autonomy, continuity and energy. They will explained in the following section. The main idea of the Poolbuoy system is to ensure continuous flow through the system. All aspects of the concept depend on this criterion.

The gathering system does not require on-board human assistance. The vessel that carries the suction head is a remote controlled vessel operated from a shore control centre (SCC). The only people operating in this concept work method are the people controlling the vessels from the SCC. Obviously personnel is required for maintenance, but for operation it will be reduced to two or three people.

A second advantage of this system is that it can run continuously over the entire year except for the scheduled maintenance of the equipment. This means that the total volumetric flow rate of the PB's are reduced drastically compared the conventional hopper dredgers. This will be elaborated in the detailed work method. Additionally, the carrying vessel is equiped with PV solar cells to generate power for the propulsion system. The propulsion system requires very little power because there is not a lott of movement. The carrier vessel is displayed in figure 14.

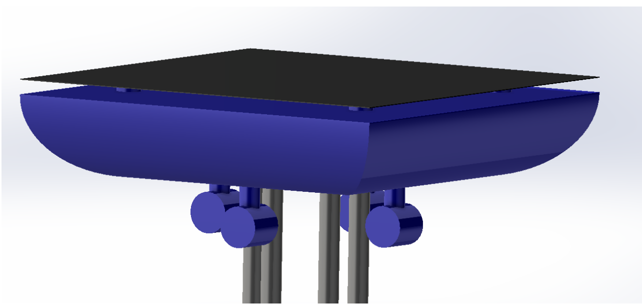


Figure 14: Poolbuoy Carrier Vessel with PV-cell on top

The carrying vessel can use a battery pack or a hydrogen fuel cell as energy carrier. This will depend on the economic suitability of both systems. The total installed power of the carrier vessel is low because it will not have to sail at high speeds ad will mostly use the tidal currents when manoeuvring. The entire pumping system in powered from the gathering point. This station is connected to the grid and distributes the energy over the pumps present in the system. By connecting the system to the grid, the pumps can run on electricity. This enables the use of renewable sources. Boskalis has to account for the electricity by investing in renewable energy projects such as offshore wind farms. The applicability of this concept is very limited as it can be applied only in the area where it has been designed to operate, if other harbors in the world would like to apply this method they would have to redesign this concept according to their needs. Also all the stakeholders involved should evaluate whether the end of the contract for the maintenance would mean to dismount the whole structure.

6.2.2 Detailed work method

The to be dredged material for the entire Maasgeul 0-6 equals $200.000m^3$ each month. This is multiplied by four to decrease the concentration of sediment in the mixture. This is done to prevent blockage. the This boils down to at least a volumetric flow rate of $\dot{Q} = 0.02m^3/s$ for each PB. Remeber there are four in the Maasgeul0-6 area. The volumetric flow rate is displayed in equation 2, where V is flow velocity through the pipe and A the cross-sectional area of the pipe.

$$\dot{Q} = V * A \tag{2}$$

The flow velocity has to be strong enough to prevent blockage by settled sediment in the pipeline system. The area of the pipeline will also have an influence on the ability of the transported material to settle. According to Boskalis' supervisors a first rule of 2.5 m/s can be used to determine the cross-sectional area of the pipeline. Using 2.5m/s would result in a radius of at least 0.1m. A larger radius is probably preferred to make sure the relative wall roughness is decreased. A narrow tube of 20cm wide and 800 meters long is not a suitable combination. A larger radius can be used if the suspension is even further diluted. Some additional research must be performed on pressure drop over such slender flexible tubes. According to Thijs Schouten, PhD candidate at TU Delft, wear and pressure drop in corners of pipeline systems will pose serious problems regarding blockage and maintenance.

Estimated installed power for pumping

A reference MEMO of Boskalis has been used to estimate the required installed power to power the PB pipeline system. For the reference, a horizontal pipeline of 13.5 km, diameter 0.65m and flow rate of $500m^3$, required an installed power of 2200kW.The installed power is multiplied with a factor 1.2 for increased pressure loss in curved systems and multiplied with another factor 1.2 for the vertical displacement to the water surface. The total amount of sediment to be removed per hour equals $555m^3/h$. Therefore, the installed power is again multiplied with 1.2 to estimate the power required for the total amount of sediment.

The total installed power for this system equals $3.8 * 10^3$kW. If this machine runs an entire month to dredge $400.000m^3$ of sediment, the total power per cubic meter of sediment becomes 24.6 mJ/M^3. This value must be multiplied with another factor for diluting the sand-water mixture that runs through the system. So a estimation of the required energy per cubic met ranges between 50 and 100 MJ per cubic meter sediment. This means it is 4 to 6 times as energy consuming than a conventional hopper.

6.2.3 Remarks

- **Carbon footprint & sustainability**, The energy consumption of this concept work method was calculated to be 50-100 MJ/m^3. This is excluding the transportation of the sediment to the dumpsite. This value can be neglected compared to the energy consumption of the pipeline system.

- **Interference, risk & safety**, The carrying vessels of the PB system will be connected to the suction heads and the main pipeline system at all time. Therefore, it is restricted in manoeuvrability. It is also exposed to risks of high waves because it is unable to sail to a safe part in the harbour.

- **Reliability**, The PB system is contains some obstacles to overcome. The flexible tubes that connect the suction head to the main pipeline system are vulnerable to wear in the corners. This means the system must be monitored closely and maintenance is a regular phenomenon. Additionally, blockage in the flexible tubes is a factor the decreases the reliability of the concept.

- **Cost**, The initial investment for the placement of a pipeline system is estimated at €2 million euros per km (Kaiser, 2017). This comes down to at least €25 million. The autonomous barges, gathering point, suction heads and carrying vessels add up another €20 million. The total CAPEX adds up to 45 million euros. As a result of the high amount of energy consumption, the OPEX is estimated to be in the same order of magnitude of conventional hoppers.

6.3 Hydrogen powered ship (H2indenburg)

This method is the most similar concept to the conventional TSHD. The two main differences are that everything is powered by hydrogen and that the orignal hopper is splitted. There is a suction ship and a transportation ship. The latter is the autonomous barge of section 5. One of the energy saving methods of this ship is that during the dredging it always operates with the tides such that it is being pushed by the currents in the longitudinal direction.

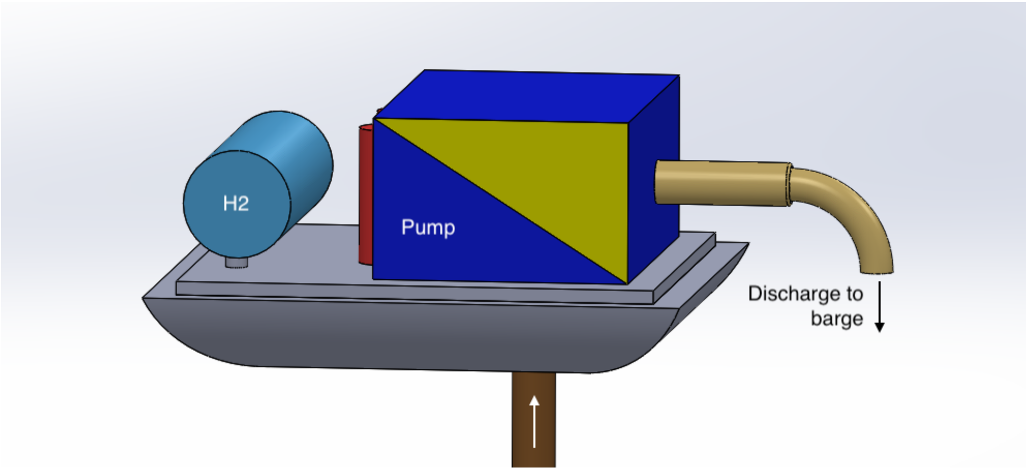


Figure 15: Hydrogen powered ship

6.3.1 Advantages

This method would very much convey with the Port of Rotterdams mission to become the worlds number one Hydrogen hub. Accordng to current plans, by 2030, a port wide Hydrogen network providing green hydrogen should be in place (Weterings, Randolf, 2020). Another advantage is that there is no need to alter the technique used in hoppers much, making this method easy to realise. This concept is widely applicable in any other Ports as the work method is similar to the traditional hopper dredger and it is easy to adapt to any type of area that needs regular dredging.

6.3.2 Detailed work method

The suction ship has the primary task to dredge the required volumes. The dredged material is discharged into the accompanying autonomous barge, see figure 16. The suction ship for now has similar equipment as the TSHD does. This means that there is a pumping mechanism ($\approx$ 3500 kW) and a propulsion mechanism ($\approx$ 3000 kW). These numbers are probably a bit on the high end as the ship will be smaller and lighter than a conventional TSHD as it will not transport the sediment. If like the TSHD the HPS will dredge with a discharge of 2400 m^3/h, it would be in operation for 6 hours a day. This requires an amount of energy equal to $6 \cdot 3600 \cdot 3500 = 76000$ MJ. This can also be expressed as $(3600 \cdot 3500 + (3000/2))/2400 = 7.5\ MJ/m^3$. On top of this there is the required energy for propulsion. As mentioned, during dredging the ship is mainly pushed by the current, the propulsion is therefore used for traveling from and to the Hydrogen tanking site. This is assumed to be a 5 km distance with a speed of 5 m/s and thus taking 1000 seconds using the 3000 kW propulsion. Propulsion energy adds up to an energy usage of 6000 MJ. The total amount of energy usage during 6 hours of dredging adds up to 82 000 MJ. Liquified hydrogen has an energy density of 8 MJ/ℓ which means if we assume a daily tank stop, the on-board tank needs to be $82000/8 = 10m^3$. This is large but not impossible. However if this tank size is considered to be too large, pumps having a lower discharge and thus lower required power could be used. This yields longer required operational times but as shown in the above calculation operational time needed was only 6 hours per day, there is definitely time for this. If for example three tank stops were introduced, a hydrogen tank of about $4m^3$ would be sufficient.

During this 6 hours of dredging 14 barges could be filled, meaning that 7 barges would be required as the round trip travel time to the dump site is 3 hours. As shown in section 5 this adds another 7 MJ/m^3 to the method.

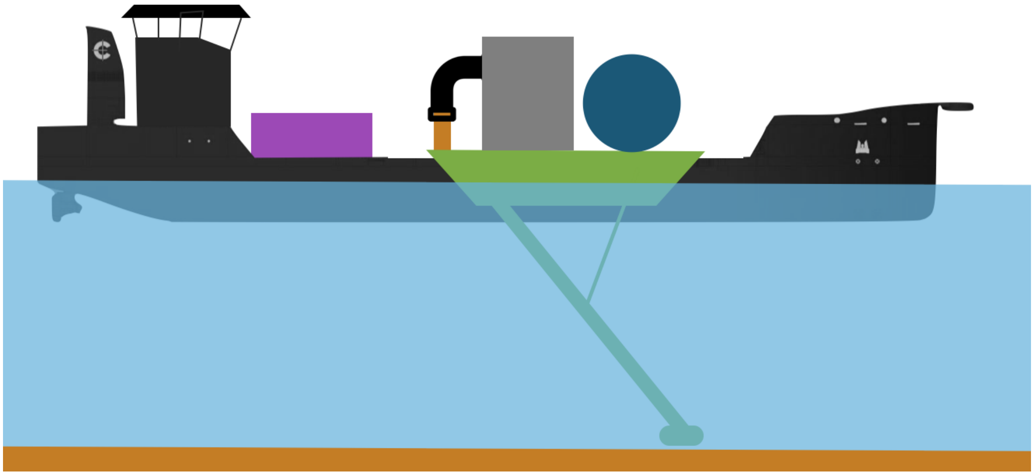


Figure 16: Full display of concept

6.3.3 Remarks

- **The energy consumption** is in line with the energy consumption of a traditional hopper dredger since the two methods are similar to each other: Energy consumption 14.5 MJ/m^3. Regarding *emissions during construction*, the ship will be of a similar size as Boskalis' Strandway, which has a gross tonnage of 4300 t. Assuming that everything is steel, this equals emissions of $4300 \cdot 1.85 = 8000$ $ton\ CO_2$. This is excluding the assembly of the ship.

- **The interference** with traffic is not very high as the ship is very maneuverable. *The human threat* is higher compared to other, autonomous, methods as this method requires a crew (like on a normal hopper dredger).

- **Robustness**. A good thing is that it is a very robust method as it is comparable to the very robust hopper dredger that although it breaks down often remains operational while it is fixed.

- **Costs**. Hydrogen cells costs are around 40 $/kW (Energy.gov, 2018) which adds up to (3500+3000) $[kW] \cdot 40\ [\$/kW] = 300\ 000\ \$$. Liquefied hydrogen tank costs, according to Derking (2019) (Utwente), are 300 euro / kg H_2. For a 10 m^3 hydrogen tank, with liquid hydrogen density being 71 kg/m^3 this results in $10 \cdot 71 \cdot 300 = 213.000$ euro. On top of this there is of course the production cost of the ship itself including dredging and propulsion equipment, this is estimated to be about 50 million euros. Regarding operational costs, they are assumed the same as the hopper dredger: €50.000 euro per day.

6.4 Shark Teeth Trailer (STT)

For this method the gathering of the sediment is done by containers on rails. These containers go over rails on the bottom of the river, helped by tidal energy, collect the sediment and then dump it at a central location. From there the sediments are pumped up using a punaise-like permanent pump and discharged onto autonomous barges.

6.4.1 Advantages

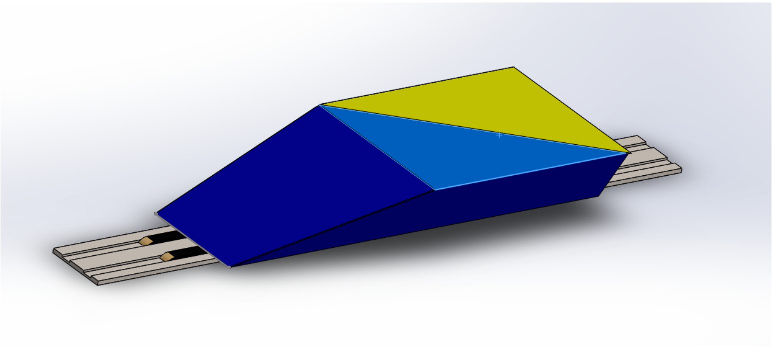
The main advantage of the STTs is that it is able to work autonomously underwater, without interfering with traffic, round the clock. Furthermore, by using the tidal currents to push the trailers, energy is saved. Capital costs are on the high end but once in operation, operational costs will remain relatively low, partly due to the low energy usage as shown later. The flexibility of this concept is limited as the rails are very specific on the area that needs to be dredged, if this concept has to be applied somewhere else than the Port of Rotterdam a complete redesign of the work method is needed. Hence the success of this concept comes from its highly specific design for the area.

6.4.2 Detailed work method

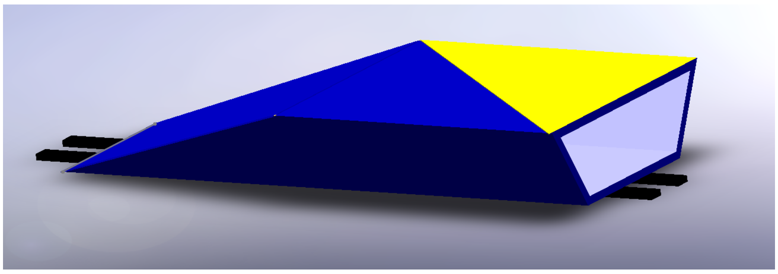
The trailer device is used for the collection process. The name "shark teeth" comes from the shape of the bathymetry that the trailers leave behind when following its path. The trench and the side slopes that are formed remind of the shape of shark teeth.

The trailer dredger consists of two parts:

1. *The Bullet head* placed at the front to navigate through the muddy bottom of the sea.
2. *The Container tank* with the purpose of collecting sediments first and next unloading them using a mechanical internal wall that pushes the sediments out of the container when it reaches the collection site.



(a) STT on rails



(b) STT rear view

For this method the dredging site is divided into sub-areas of approximately 2.5 km. The rails are going to operate along the lengths of these areas, leaving a narrow corridor in the middle to let the bigger ships sail freely in and out the Port of Rotterdam waterway. The trailers are going back and forth on top of the rails. During the ride the bullet-head (front) is used to push the mud from the rails, then the second ride is backward so that the tank can be gradually filled up with the sediment. At the end of the second ride, one cycle is finished and the sediments can be unloaded onto the pumping mechanism. The lengths of each dredging area and the number of collection sites per area are hereby listed:

Name of the area	Length	Collection sites	Dredging target per year
Maasgeul 0-6	5km	4	2.250.000 m3
MAMO-F	2.5km	2	250.000 m3
MAMO-E	2km	2	2.000.000 m3

Given the length of Maasgeul 0-6, there will be two collection sites: one in the middle and one at the border with MaMo-F. As previously stated, at each collection site there will be a number of Punaise pumps. Considering the big amount of sediments that needs to be removed and the limited dimensions of the trailers needed in order to avoid any interference with marine traffic, it is required the installation of several trailers parallel to each other. The shape of the tank is a trapezoid and depending on the length of the lower and upper side an angle will form that will generate a more or less steep slope on the seafloor in which the sediments will roll and flatten out. The dimensions of each trailer tank have been calculated to be as follows:

- Height: 1.86m
- Upper side: 12.85m
- Lower side: 2.82m
- Angle between horizontal and upward plate [θ]: 21°
- Tank cross sectional area: 14.50 m^2
- Maximum capacity of the tank: 362.68 m^3

The dynamics of the filling up process of a movable underwater tank is hard to predict as a consequence the tank will unlikely be completely filled up (real efficiency $<$ Max. capacity) but given the low speed of their movements, good chances are that at least 50% of the tank will be filled. The calculations performed takes that into consideration and randomized the efficiency of the trailers between 20% - 80% in order to have a safe and realistic result. The average capacity of a tank is between 180 - 220m^3. Consequently, knowing the mean density of the sediments (ρ_s) and the density of water (ρ_w) it is possible to account for the buoyant underwater force and retrieve the actual mean mass of the trailer at the bottom of the canal:

$$M_{STT} = (\rho_s - \rho_w) * volume + (\rho_{hdpe} * V_t) \approx 74000N \quad (3)$$

where the product of ρ_{hdpe} * V_t is the mass of the structure itself and it is estimated to be equal to 15% the mass of the sediments. (ρ_{hdpe} = 940 kg/m^3)

Use of tidal energy

This concept makes use of tidal energy for the movement of the trailers, this way the trailers are forced to operate for six hours in one direction. One full cycle will take approximately 12 hours, this allows the trailers to complete two cycles over an entire day and if we consider the average capacity stated above, each trailer will be able to transport a theoretical amount of 400m^3 per day. It is calculated that in order to be able to reach the dredging target every year, 10 STT's have to be deployed on each side of the dredging area. 90% of the yearly volume of sediments is located inside Maasgeul 0-6 and MaMo-E, these areas will have a total of 40 operational STTs inside each of these areas, while MaMo-F will only use 20. The total number of STT's deployed in the Port of Rotterdam will be 100 (see fig. 19). This large number of trailers is able to dredge the total required amount of sediments in less than a year: it is operational for roughly 290 days a year leaving 75 days available for downtime/maintenance when needed (see fig. 18).

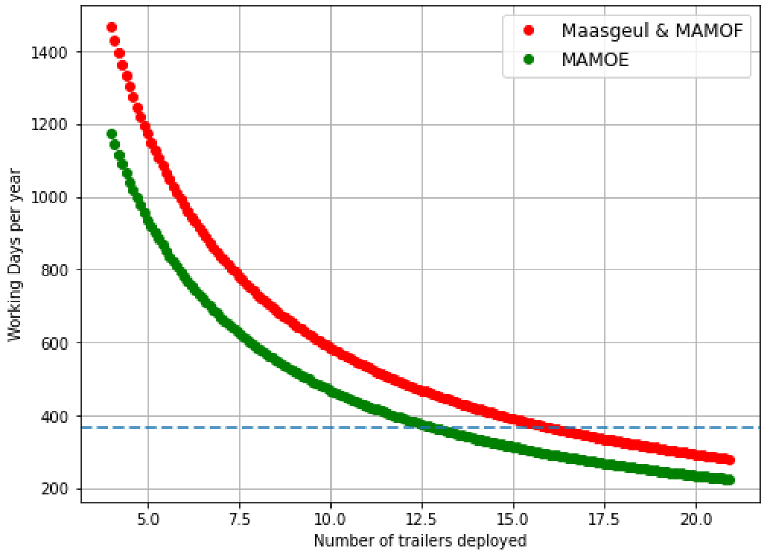
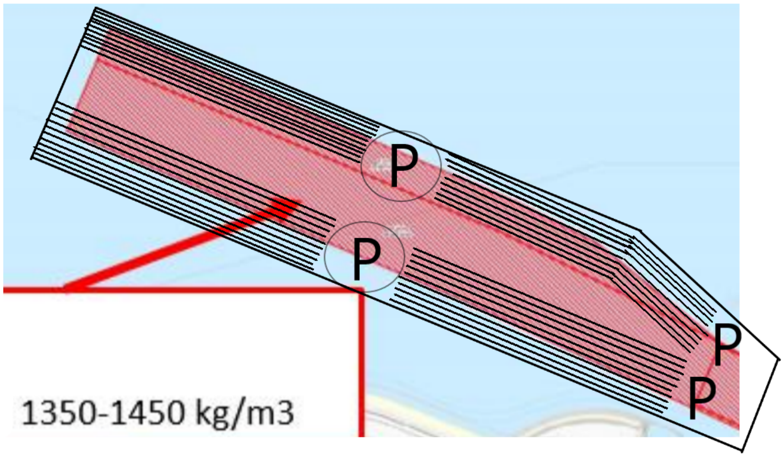
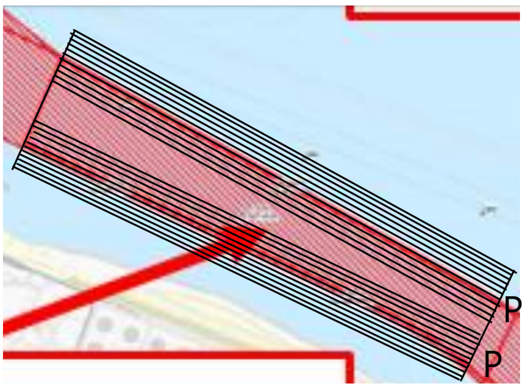


Figure 18: Working days per year vs. Number of trailers deployed



(a) Maasgeul 0-6



(b) MAMO-F

(c) MAMO-E

Figure 19: Trailers operational areas

Since the vertical profile of the tidal current inside the canal has a logarithmic profile, the available energy at the bottom will be much lower than at the surface, the speed of the trailers has to be 0.11 m/s in order to span through the entire length of the rails during one tidal cycle.

This speed allows us to calculate the drag force applied to the trailers using the drag equation:

$$F_D = \frac{1}{2} * \rho * U^2 * C_d * A \tag{4}$$

C_d is the drag coefficient and is a function of the Reynolds number (Re). The characteristic length scale for the trailers is given by the length-to-height ratio, which in this case is $25/1.86 = 13.44$, then the Reynolds number can be calculated using the mean density of the mud ($1350kg/m^3$) and the kinematic viscosity $1 * 10^-6m^2/s$. These numbers leads to $Re = 8.3 * 10^5$ which corresponds to a drag coefficient of roughly $C_D = 1.1[-]$. The drag force can then be easily calculated and is related to the power consumption due to the velocity of the trailers:

$$P = (F_{drag} + F_{rolling}) * U = 885W \tag{5}$$

$$E = 885 * dt = 40 * 10^6 = 40\text{MJ} \tag{6}$$

$$\frac{40MJ}{\text{mean volume of trailer}} = 0.17MJ/m^3 \tag{7}$$

Once the sediment is gathered at the chosen location, they have to be lifted with a hydraulic pump (and its capacity has to be able to dispose within one tidal peak time as much sediments as the STT's are delivering in one ride.

In short, each pump capacity has to get rid of $4000m^3$ every 24 hours, which leads to an hourly rate of $170m^3$ per hour. The dominant flow rate of the Punaise will be roughly $\dot{Q} = 0.05m^3/s$. From the literature, the power consumption of the Punaise pump used during the experiments in the 90s was 1200kW with a pump capacity of $800m^3/h$ (PN250). For this work method, the pump capacity required would be only 21% the capacity of the PN250 as the sediments are gathered more slowly. Therefore the power consumption of each Punaise is 252kW. Since some pumps are placed further away from shore, friction losses must be taken into account using Darcy-Weisbach equation. Using a pipe diameter of 0.3m, $\dot{Q} = 0.05m^3/s$ and knowing the average density of the sediments, the friction losses over the pipeline equals to $265Pa/m$.

6.4.3 Remarks

The energy consumption required for the collection of the sediments has been calculated by making some assumption: Rolling resistance coefficient $C_{rr} = 0.01$ (train on steel rails) although this is unlikely to hold underwater where the rail surface might be contaminated with silt.

The speed at which the trailers have to move is very slow and it is generated by the tidal currents inside the canal which vary from 0.25m/s in the inner compartment E up to 1.0m/s in the northern branch of the Maasmond (Verlaan, 2000), the calculations performed used a speed of 0.11 m/s which is enough to ensure the coverage of the total area. The values above are *vertically* averaged speeds which means that in reality, chances are that the tidal current at the bottom will not be enough to push the trailers, therefore this concept will be combined in a later stage with other mechanisms e.g. use of a tugboat to push the trailers from the surface.

- **The energy consumption** during the collection part is around 0.2 MJ/m^3 which makes this concept very efficient for gathering. The overall energy consumption of the entire process: $0.17 + 5.4 + 7 = 12.6MJ/m^3$. The *emission during construction* are calculated using COR-TEN steel as main construction material for the rails which is widely used in maritime shipping transportation. The amount of steel needed to cover 180km of rails is roughly 11000 tons, pillars to hold the rails to the bottom must be accounted for and they should be sufficiently deep to assure stability and reliability. Cylindrical perforated pillars (r=2m, h=10m) are deployed with a distance of 125m from one to another, making the total amount of the steel 23000 tons. Emissions during construction are therefore estimated around 45 kilotons of C02.
- **Interference with traffic**: Interference with maritime traffic is on limited, given the reduced height of the trailers and the fact that this concept is a permanent underwater structure shoveling at the bottom of the canal. *Human threats* are significantly high during the construction part and during maintenance given the harsh environment in which the rails have to be installed. During operation these threats are minimum as this concept is unmanned. The *level of autonomy* for the collection part is classified at level 4 - Fully autonomous (DoD levels), while for the pumping part is at level 3 - Human supervised.
- **Robustness**: This concept, if proved feasible in the near future, could be robust. Its weaknesses for now are the installation of the underwater rails and the use of tidal energy. This challenges can be solved by applying some variations to the concept. These variations will be discussed later. The underwater rails

need periodic maintenance since the sea water is highly corrosive, the tidal energy is weak at the bottom and if larger debris settle on the rails the trailers would not be able to carry out any operation. *TRL*: The technology behind this concept already exists, but its usage underwater makes it more difficult to implement and more research is needed in the future in order to assess the possible implementation.

- **Costs**: Steel rate as of 2021 is around 600 €/ton. This steel needs to undergo a weathering process in order to be more durable underwater. Even so, periodic maintenance of the rails is still required given the high level of oxidation in seawater. The price of the steel needed just for the rails hovers around €14 million. This number does not consider the installation costs (man-work + machinery) which is presumed will make the price easily to skyrocket at least to €50 million. The trailers are made of thick plastic so they will not need lot of maintenance and the installation costs should be relatively low. The CAPEX ≈ €80-100 million. The OPEX consist of powering the Punaise pump: from (Visser & Bruun, 1998), 20 years ago - unit cost of the Punaise was 3 euros per m^3 of dredged material. Since this figure is outdated now and the Punaise will be connected to the grid, furthermore the pump capacity required is only 21% of the pump used in the 90s, it is expected that the price per month will not exceed €250.000 per pump, where a total of 8 pumps is needed.

6.5 Lifting rugs (LR)

This concept work method is based on the idea that sediment will slide along a slope to its lower point. At the end on the slope a pit is located, where a fixed dredging pump is located. First the overall operation is explained and the advantages of a concept like this are stated. Later the details are provided and remarks are given.

Overall operation

The rugs at the bottom of the canal are normally horizontal and when a layer of sediment is formed on top of the plate it tilts, causing the sediment to slide to the lower side. Due to the configuration, see figure 20, of the plates the sediment will end up in several collection pits, where the silt-sand material will be dredged into a barge. The sailing direction indicates that the dredging pit is located at the sides from the canal and the dotted line represents the midway line. First the rugs adjacent to the dredging pit will tilt, followed by the next rugs in line, etc. This lifting of the rugs can happen at any time so the process could be continuously, minimizing the sediment layer weight. After one week the layer of sediment will be approximately 1 cm overall, but due to the settling behaviour of the sediment more will settle towards the sides of the canal. Therefore the rugs towards the sides are smaller as they need to lift more weight. Finally the dredging pit is emptied with a fixed pump, for simplicity we consider the already mentioned Punaise pump.

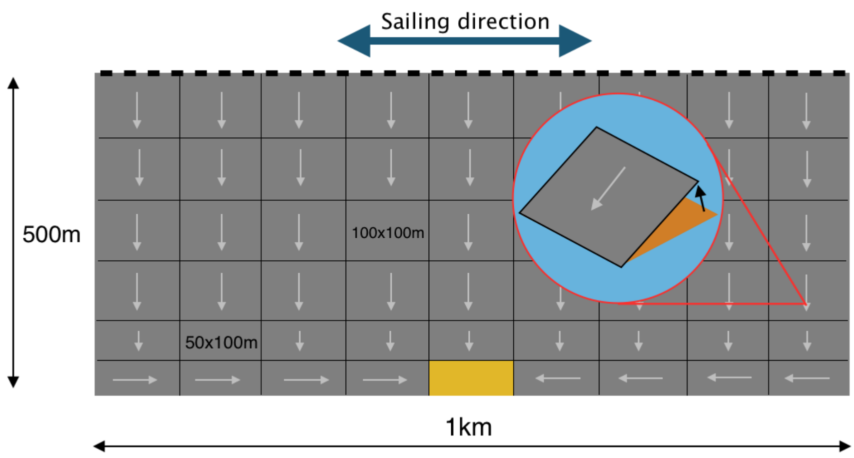


Figure 20: Schematic impersonation of lifting rug concept. The yellow tile being the dredging pit.

6.5.1 Advantages

A permanent slope in the bed leads to lowering the bottom beyond the required 26 meters. This deeper canal would cause more sediment to flow in again, because of the tidal amplification (D.S. van Maren, 2015) which brings in more sediment with each tide. With this concept work this phenomena is avoided and less sediment has to be dredged. The concept work method is also able to work continuously as the rugs lift themselves with a certain time-interval. This interval can be adjusted in such a way that the rugs do not tilt too often, resulting in an excessive energy consumption, and will tilt often enough so the weight on top of the rugs is not beyond endurance. The bulk of the process takes place underwater causing minimal interference with the traffic in the Maasgeul and Maasmond, only the transportation barges have the cross this fairway.

6.5.2 Detailed work method

It is assumed that the sediment will start sliding when the rugs are inclined at an angle of 15°, as the maximum repose angle (the angle that material will maximally generate when it is dropped from above to form a pile) of water saturated sand is between $15-30°$, (Hamzah M. Beakawi Al-Hashemi, 2018). As the sediment is also partly silt, being more free-flowing and the contact of the material experiences less friction from a smooth plate, the assumed angle of sliding is 15°. With this configuration the bigger rugs located towards the centre of the canal need to be lifted 26m from the seabed, just staying submerged. The rugs are made from a stiff material, averting to bend in the middle and leading to sediment not to slide. The material needs to be light, strong and unaffected by the seawater. Therefore a polycarbonate, widely used thermoplastics, is used in this case. The materials has a yield strength of 60-70 MPa and a density of 1220 kg/m^3, having a slightly higher density than water. To check if the material is strong enough some calculations are performed. The maximum expected bending moment and thus bending stress will take place in the larger rugs with the most sediment on top. Hypothetically, a 100x100m polycarbonate rug with a thickness of 2cm and a 3cm thick layer of sediment settled on top, experiences a maximal stress of 30 MPa when simply supported on both sides.

The rugs are lifted by the force of buoyancy. At each side of the rug that needs to be lifted a cylindrical shaped tube with a diameter of 0.50m is connected on top of the rug, shown in figure 21. When the rug needs to be lifted, the tube is slowly filled with air, generating lift. This manner of lifting omits any lifting system underwater in the form of pumps, motor or rails, making it more robust. When the rug needs to be lowered the air is simply let out, filling the tube with water again.

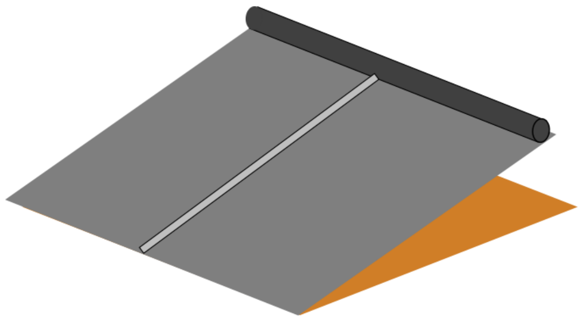


Figure 21: Floatable pipe on rug

This way of lifting induces a pipeline system underwater with pumps on the side to be able to fill the lifting tubes for every rug individually. The force to lift the rug can easily be calculated and therefore the energy used per cubic meter to transport the sediment to the pit can also be determined. Some sediment will have to be transported further, but it averaged out on roughly 1-2 MJ/m^3. This does not include the frictional losses in the pipeline-system. The Punaise-Pump requires around 5 MJ/m^3 (see Chapter 5), for a total energy consumption of 6-7 MJ/m^3 for the dredging of the sediment.

6.5.3 Remarks

At first glance, this concept looks promising. But considering that the entire area of 10 km^2 needs to be covered with polycarbonate rugs, this can not be efficient. An alteration on the configuration could be that only parts of the seabed will be covered with the rugs, for instance the sides of the canal only. The use of buoyancy as lifting force looks useful, because no delicate moving parts are needed in the harsh underwater environment.

- **Carbon footprint & sustainability**, the energy consumption for the dredging of the material looks promising as it only uses around 7 MJ/m^3 to dredge the material from the bed of the canal into the transportation barge. The *emission during the construction* will be on the higher side as difficult operations need to be performed, like correctly placing the rugs on the seabed. For the configuration as it is right now a total volume of 0.2 million cubic meters of poly-carbonate is needed. This results in a total weight of 244.000 tons for only the rugs. The energy used to produce 1kg of poly-carbonate is around 100 MJ (Boustead, 2005), or the equivalent of burning 0.5ℓ of crude oil.
- **Reliability**, the *robustness* of the entire concept is high. There are no moving parts underwater and the air pumps are installed on land, so maintenance on these pumps is easy. The material of the rugs does not react with water and this can even be improved by applying a non-reactive layer of paint. All the required *technologies* are all well known so will not bring any uncertainties.
- **Interference, risk & safety**, the concept has quite some interference with the traffic in the Maasgeul and Maasmond as the rugs will be lifted to just under the water level, this can temporarily cause disturbance in the already busy waterway.
  However the exact configuration can be altered to an optimal size and angle to minimize the impacts. The time for a rug to go up will be around 6 minutes, going down can be done faster.
- **Cost**, the costs of the project are mostly in the material of the rugs, being ≈0.5 euro per kilogram (Plasticker, 2020). Resulting in the cost of €170 million. The pumps, pipelines and installations costs are not included in this.

6.6 Fully autonomous submerged dredger (FASD)

This concept makes use of fully autonomous submerged dredgers (FASD's), where on first glance a lot of advantages arise regarding energy consumption, interference with traffic and safety. First the overall concept is explained, then the advantages are touched on upon and later an initial concept is worked out.

Overall operation The work method consists of one or more submerged autonomous dredgers, shown in figure 22, powered by lithium-ion battery packs. These dredgers are constantly sucking up the sediment trough a suction hose, gathering the sediment in the basin. Filled up, the autonomous dredger will sail towards the dump area where it will dump the sediment by opening its bottom hatches. When the battery-pack is running low, the dredger will sail towards its charging station somewhere in the Port of Rotterdam, ready to continue doing maintenance dredging after it is charged. The dredgers are as simple as possible, they can sail, have a basin, a suction pipe, a pump and an autonomous sailing software implemented.

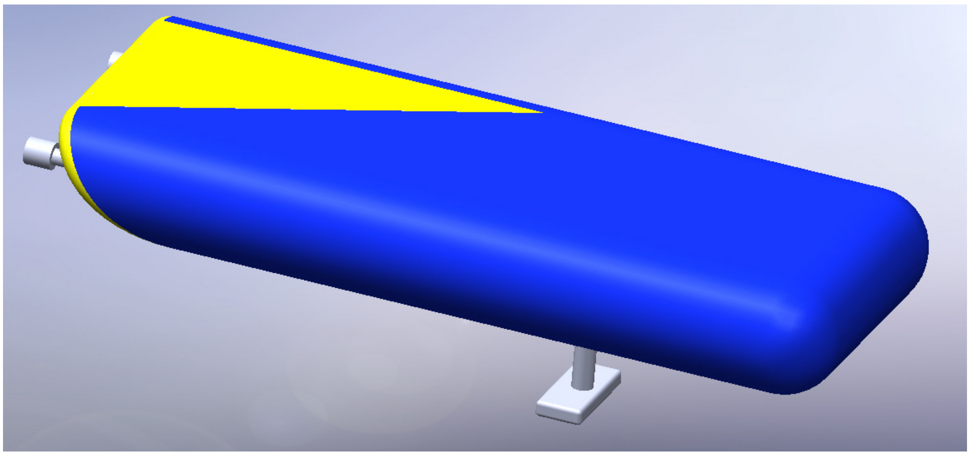


Figure 22: First impression of the autonomous submerged dredger

6.6.1 Advantages

Being submerged, the dredger does not interfere with incoming and outgoing traffic as much as the conventional dredger. The majority of the vessels do not cross paths with the submerged dredger as this sails around 5 meters above the bottom of the port. The vessels with largest draught ($\approx$ 26m) will sail in the middle of the entrance. Here the least sediment will settle due to the disturbance of the screw so the amount of time spent in this area is, like the conventional TSHD, limited. This reduction of interference also lower the risk of possible collisions, being safer for the traffic in the Maasgeul.

Due to the fact that the submerged dredger is closer to the river bottom the amount of energy needed to dredge the sediment into the vessel is lower. This can be seen in the equation for the required installed power (8), where Q_{in} is the inflow speed of the mixture of sediment and water $[\frac{m^3}{s}]$, ρ_m is the density of this mixture $[\frac{kg}{m^3}]$, η is the efficiency [-], g is the gravitational acceleration $[\frac{m}{s^2}]$ and h is the height between the suction head and the sediment basin in the dredger $[m]$.

$$P_{pump} = Q_{in} * \rho_m * g * h * \eta \qquad (8)$$

A conventional dredger has to suck the mixture over a height of $\approx$26m, quadrupling the required pump power. Finally we see that a submerged vessel experiences significantly less resistance from the water, as the vessel is not subjected to the forces of the waves.

Since the submerged dredger is autonomous, no crew on the vessel is needed. This enhances the overall safety of the work method, but more importantly this enables the use of renewable energy to power the dredger. As the supply of renewable energy is not constant the submerged dredger is not always able to dredge. Being autonomous it can dredge whenever the supply of renewable energy is sufficient. Also the reduced size and thus installed power enables the use of batteries. This concept is probably the most flexible work method discussed in this report. It does not require the installment of any fixed structure and it can sail autonomously to the dump site making this work method widely applicable anywhere it is desired, the only restraint comes from the water column height which might be an issue in case it is too shallow.

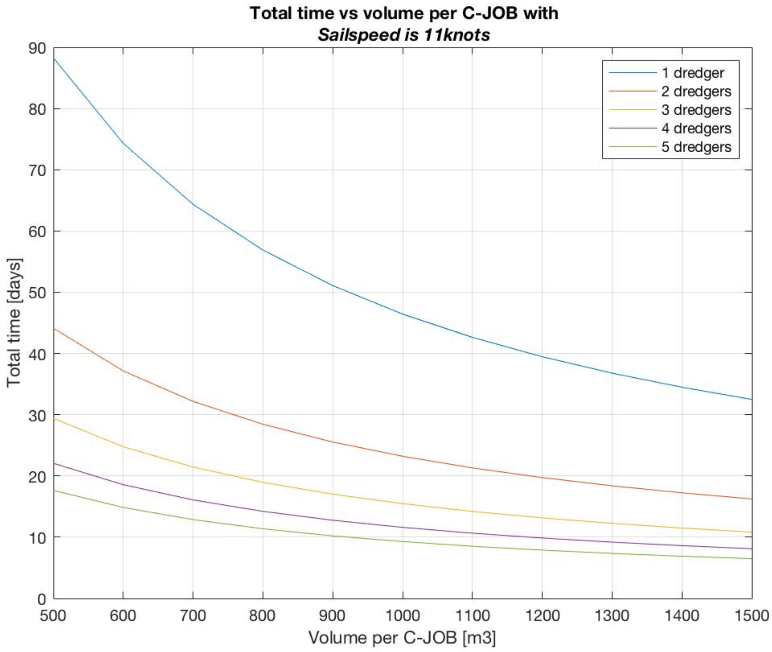


Figure 23: Plot to determine initial parameters of autonomous submerged dredger.

6.6.2 Detailed work method

To check whether the concept is feasible and in what configuration it is performing optimal, an initial detailed work method is analysed. The preliminary size, number of dredgers, total trip size, installed power and required energy per cubic meter of sediment are determined. This will give a better overview of the exact characteristics of the autonomous submerged dredger. To determine the size and the amount of dredgers required we first assume that the dredgers work 100% of the time, sail with a reasonable speed of 11 knots and have a inflow velocity of $1m^3$ of sediment per second. Then the volume per dredger and the amount of dredgers is varied, the results are shown in figure 23. Here it can be seen that for three dredgers with each a volume of $700m^3$, it takes approximately 22 days per month to complete the job. Considering charging time and downtime, one could expect that 3 dredgers with each a volume between $700m^3$ and $900m^3$, depending on charging time and downtime, would be suitable for the maintenance dredging. The overall dimensions of the basin in the dredger are: length is 25m, width is 10m and the height is 4m, so the volume of the basin is $1000m^3$. This way the basin does not have to be filled up entirely to ensure the capacity of sediment. Due to the overflow mechanism, the basin can not be fully filled.

The FASD is engineered in such a way that it will hover in the water when not filled with sediment, this is endorsed by filling some of the water tanks in the FASD with enough water or air that this vertical equilibrium is guaranteed. When the submerged dredger is filling up with sediment, the weight of the dredger will increase. To still be able to hover and not sink to the seabed, extra buoyancy needs to be created. This can be done by trusting in a downward direction, but can also be done by filling some of the airtight water tanks with air. If the dredger is fully filled with sediment, an additional 300 tons of mass needs to be lifted, resulting in an extra needed buoyancy force of 1.4 mega-Newton. This is shown in equation 9.

$$F_B = V * (\rho_{sed} - \rho_w) * g = 800 * (1400 - 1025) * 9.81 = 2.9MN \tag{9}$$

Thus 2.9MN of lifting force needs to be created, resulting in a volume of $294m^3$ of air. Due to the shape of the dredger, see figure 22, the room available at the sides of the dredger is about $350m^3$ when tightly designed. The shape of the FASD is designed in such a way that the ratio between the length and frontal area is according to (Moonesun, 2016), being between 7 and 10. This is for submarines with a straight cylindrical middle shape, where the drag coefficient is given to be 0.3 (Joubert, 2004).

To calculate the energy required to pump the volume of $294m^3$ over a depth of 25 meters equation 8 can again be used. An additional 0.38 MJ/m^3 is required to dredge the sediment and transport it to the dump area.

Table 1: Initial parameters of the autonomous submerged dredger

Autonomous submerged dredger characteristics			
Time per trip [min]	165	Inflow speed $[m^3/s]$	1
Dredging capacity $[m^3]$	800	Drag coefficient [-]	0.3
Sailing speed [m/s]	5.66	Energy consumption $[MJ/m^3]$	6.84

To get a good view on the demanded battery capacity it is assumed that 3 submerged dredgers each with a volume of $800m^3$ are used. The characteristics of these dredgers are given in table 1, where it can be seen that the energy consumption per cubic meter of sediment is significantly lower compared to the conventional TSHD. Then, to make it easy for the initial calculations, we fix the required battery capacity to be sufficient for 2 trips. Then, because of the amount of dredgers, it has the time required for 1 trip to sail to the charging point and fully charge. For the trips the total energy capacity can be calculated and with the energy density, see figure 24, the total volume of the batteries is defined. With the cost per kilowatt hour according to BloombergNEF (NEF, 2019), being 100euro per kWh, the costs of the battery-pack can also be determined.

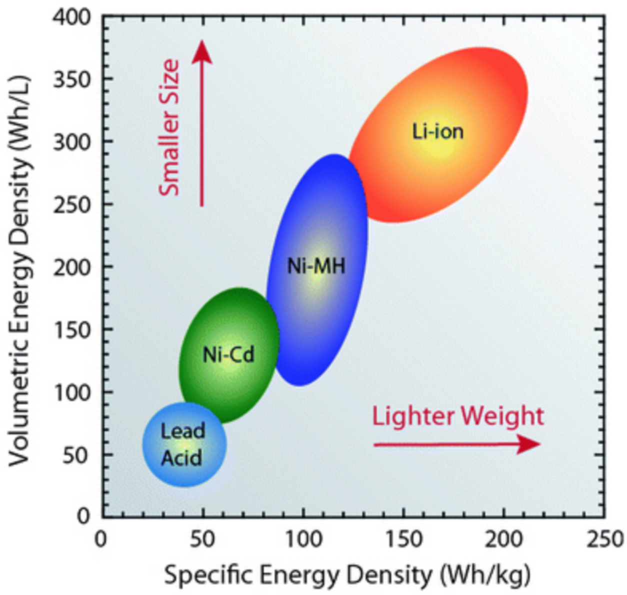


Figure 24: Energy density of different batteries. Source: (Epectec, 2020)

For now the work method consists of 3 smaller autonomous submerged dredgers with a capacity of $800m^3$. To dredge the sediment and transport it to the dump area for 2 time, a total battery capacity of 3362 kWh is required, resulting in a volume of $11m^3$ and a total cost of approximately €330.000 euro for the battery pack. The battery-pack must be loaded in 2.7 hours, which can definitely be done and does not require a super fast charging device.

6.6.3 Remarks

On first glance the FASD looks very promising, as only about 7MJ is used per cubic meter of sediment dredged and transported. This is due to the fact that the resistance is limited, thanks to its optimal shape and ability to operate completely underwater. At this stage the dimensions of the FASD are not enable to hold the needed additional air to create buoyancy, so it will have to be redesigned. Besides the necessary vertical equilibrium, the shifting centre of gravity of the liquid load also induces a problem. The filling of the different airtight tanks needs enforce stability in the roll direction. This causes a big engineering problem to overcome, but is not impossible.

- **Carbon footprint & sustainability**, the energy consumption per cubic meter is estimated to be only 7MJ. The emissions during the construction are also limited in comparison with the other concepts, the CO_2 emission of lithium ion batteries lays between 39 and 196 kg per kWh (Melin, 2019). Resulting in a total emission of 1700 tons of CO_2 during the construction of the batteries. Further is is estimated that the dredgers require an amount of approximately 2000 tons of steel, for which 3700 tons of CO_2 is emitted. The environmental impacts of the FASD are similar to that of the conventional TSHD as it has the same methods of dredging. The FASD does not make use of diesel and oil to run, so the chances of this to leak are negligible.

- **Reliability**, the FASD is overall averagely reliable. Due to the electric driven motors the FASD has limited moving parts, which is positive. An issue arises with the chance of breaking down and being stuck underwater. Finally the technology readiness level of this concept is low as a navigational software for underwater environments like this are not yet available.
- **Interference, risk & safety**, as the FASD has a height of 4 meters, which will increase due to required enlargement, and hovers 2 meters above the seabed, the dredger will interfere with some of the bigger vessels. Because is also transports the sediment underwater the interference is very limited. The human threat level is also very limited because no personnel is needed and this goes hand in hand with the high level of autonomy.
- **Cost**, the total cost of the FASD is now estimated to be around 20 million euros. Given the fact that three are needed and a charging system is also required a total of 70 million euros for capital expenditures is predicted.

7 Multi Criteria Analyses

To finally come up with the most suitable concept work method, a multi criteria analysis (MCA) is performed. This MCA is a framework that assists in helping to make complex decisions. Some new concepts excel in one aspect of the entire process, whereas another aspect of the process is not performed as well. In chapter 6, the six different concepts were presented and in this chapter these are compared with each other to find out where the weaknesses and strengths of each concept lay. This is also the goal of this chapter, as with this information a targeted iteration step can be performed.

7.1 Defining & weighing the different criteria

In chapter 3 the four main categories are introduced. In order to accurately score the concepts per category several sub-criteria are established. All the criteria of the MCA are weighed: first the four main categories are weighed a percentage, where the total will add up to 100%. Then within each category, the sub-criteria will also be weighed in the same way. The total overview of all the categories, sub-criteria and their accompanying weights is shown in figure 25. The reasoning behind the weights is presented in the following sections.

Category	Weight (%)	Criteria	Abbreviation	Sub-weight (%)	Total weight
Carbon footprint, Sustainability	40	Energy Consumption [MJ/m^3]	CS1	60	0,24
		Emission during construction	CS2	30	0,12
		Environmental impacts	CS3	10	0,04
Interference, Risk & Safety	25	Interference with traffic	IRS1	45	0,1125
		Human threats	IRS2	45	0,1125
		Level of autonomy	IRS3	10	0,025
Reliabilty	25	Robustness	R1	70	0,175
		Accessibility	R2	20	0,05
		Technology Readiness Level	R3	10	0,025
Cost	10	Cost per m3 (CAPEX)	C1	50	0,05
		Cost per m3 (OPEX)	C2	50	0,05

Figure 25: *Overview of the main categories, criteria and their weights.*

7.1.1 Carbon-footprint & sustainability

The goal of this project is to design a concept work method that is efficient, but most importantly, is emission free during operation. Therefore, this category is the most important and given 40% of the total weight in this MCA.

Energy consumption per cubic meter (CS1)
A good way to achieve zero emission during operation is to minimize energy consumption as much as possible. A reduction in energy resources implies that the concept is also overall more efficient, for these reasons the criteria for the energy consumption (MJ/m^3) has the highest weight on this MCA and it counts for 24% on the overall score. It expresses the energy needed to dredge and transport 1 m^3 of sediment.

Reduction of energy consumption is in line with Boskalis sustainability report aiming for emission free operation by 2050. The reduction of energy usage will be a key process in this. Furthermore, the Port of Rotterdam has also committed to the Paris agreement, aiming to become emission free by 2050.

Emission during construction (CS2)
The maintenance dredging must be performed without emitting carbon dioxide. This restriction is for the operation of the designed concepts. All the concepts meet this demand. They differ, however, in the emission of harmful gasses during construction and installation. Using a concept with high emission in the earlier stages of the lifecycle cannot make up for the prevented emissions during operation. An assessment has been performed for all the concepts by estimating the total emission of carbon dioxide during construction of the concepts. For example, for steel it is known how much ton carbon dioxide is produced per ton of steel.This criteria is considered to be important and given a total weight of 12% of the MCA.

Environmental impact (CS3)
Conventional dredging has a large impact on sea life at the bottom of rivers. One could say that areas that are dredged frequently are 'dead'. Still, some methods are more harmful to sea life than others. Sucking up sediment at high speeds is difficult to escape, but a slow moving structure is probably less deadly as it might become a part of the river bed. This criterion also takes the risk of leakage of oil and other harmful elements into account. The environmental impact of the new concept work methods accounts for 4% of the total score. This seems very low, but as mentioned before, the canal bed is being dredged almost monthly, reducing sea life in general.

7.1.2 Interference, risk & safety

This category received a weight of 25% as it is essential for any new design, but for the sake of this project, the first category is more important. Risks and safety should always be taken into account when designing new concepts work methods as well as interference with traffic since Port of Rotterdam is an area with high density traffic.

Interference with traffic (IRS1)
The yearly dredging in the Maasmond and Maasgeul is performed to maintain the possibility for large vessel to enter and exit the Port of Rotterdam. This entrance should therefore always be preserved, also during the dredging process. Minimizing the interference with traffic simultaneously lowers the risk of collision and thus improves the safety. This criteria is weighted with a score of 11 %, which is relatively high.

Human threats (IRS2)
The risk of human threats should be as low as reasonably practicable (ALARP). This is considered during the construction, operation and maintenance. Complex underwater processes during construction create more risky situations than simpler constructions on land. The same goes for maintenance at a depth of 25 meters.During the operation the odds of collision with other vessels and their chance on human threats is also taken into consideration when scoring the concepts. This criteria receives a score of 11 % as well.

Level of autonomy (IRS3)
Autonomous methods present a couple of advantages. Autonomy reduces costs because it saves on personnel and space required for crew, it can be safer because there are no people on board that could get hurt and finally it is more flexible because it is not dependent on certain working hours. The last makes it also possible to only run if green energy is available, which again links to Boskalis' sustainability goals. However, as it is not a necessity for reaching the goal of an emission free work method, it receives a score of 4 %.

7.1.3 Reliability

The reliability of the new concept work methods should play a significant role in the MCA. The port of Rotterdam is one of the biggest ports in the world and they cannot afford to be unreachable for ships for even a single day. If a new concept breaks down and is unable to perform the maintenance, Boskalis will have to use polluting hopper dredgers to ensure a minimal water depth of 25 meters. Therefore, the reliability category has been given a weight of 25%.

Robustness (R1)
The robustness of a concept is assessed by its reliability and maintainability. Robustness is a measure of the

endurance of the machine and its complexity, it is intended to estimate the risk of downtime and failures. Concepts that require a lot of maintenance do not necessarily imply a low robustness. This depends on the amount of down time when maintenance work is performed. Conventional hoppers require much maintenance, but the majority can be done while remaining operational. Low reliability compromises its competitiveness with other methods. If a work method proves to be energy efficient but it is vulnerable to its surrounding environment then the chances of breakdowns are high. Additionally, work methods that require a lot of maintenance are in general more expensive, because they require maintenance crews. This is also taken into account in the OPEX criterion. Robustness is the most important criteria in this category and therefore receives an overall weight of 17.5%.

Accessibility (R2)
Some methods will be a lot more difficult to be maintained than others. For example, a permanent underwater structure is harder to maintain than something that is above water. Performing maintenance to a structure 25 m below water level is undesirable. It is difficult to see in that depth and it is potentially harmful to divers. The accessibility is weighted with 5% because it has some overlap with the Human Threats criterion.

Technology Readiness Level (TRL) (R3)
Generating a new concept work method with existing technology gives the executive party more confidence in the feasibility of the project. As Boskalis wants to remain competitive, it should always look into future technologies that can help them develop new dredging methods. It is of course more ideal if required technology is available, however this is no deal-breaker as technology is constantly evolving. The TRL also does not necessarily influence the emission of concepts. For these reasons, the TRL is weighted a small 2.5% in this analysis.

7.1.4 Cost

Even though costs are of great importance for listed companies such as Boskalis, this research must not be withheld by economical boundaries. The R&D department has the privilege of being able to reduce the weight of the cost category to a minimum. Therefore, this category is weighted with 10%. This way it is taken into account, but it will not have a great influence on the outcome of this MCA. The weights for the capital expenditure and the operational expenditure criteria are divided equally. They both have an influence of 5% of the total MCA.

Cost per m^3 (CAPEX) (C1)
The cost are usually the biggest showstopper for new concept work methods. For a listed company like Boskalis, the ability of making profit is in the end the most important incentive of any decision. However, the goal of this research is not to be limited to economical boundaries. The capital expenditures (CAPEX) of each concept was estimated by looking at material price and final costs of similar projects.

Cost per m^3 (OPEX) (C2)
The operational expenditures (OPEX) of each concept are difficult to accurately assess. The final OPEX will be estimated by thinking of the OPEX to be a function of energy consumption, salary for personnel and maintenance costs. Therefore the average of the criteria for energy consumption, level of autonomy and robustness are used to estimate the operational expenditures.

7.2 Results

In this section the motivation behind the MCA scores of each concept is given. For each of the criteria the most striking scores are explained.

Category	Weight (%)	Criteria	Total weight	TSHD	FASD	SWID	PB	FR	H2	STT
Carbon footprint, Sustainability	40	Energy Consumption [MJ/m^3]	24,0%	2	4	3	1	4	2	4
		Emission during construction	12,0%	3	4	5	3	1	3	2
		Environmental impacts	4,0%	1	2	4	2	3	2	4
Interference, Risk & Safety	25	Interference with traffic	11,3%	3	4	4	2	2	3	4
		Human threats	11,3%	3	4	5	3	2	3	2
		Level of autonomy	2,5%	1	4	1	4	4	1	4
Reliabilty	25	Robustness	17,5%	4	4	5	2	1	4	3
		Accessibility	5,0%	5	3	5	2	1	5	1
		Technology Readiness Level	2,5%	5	2	4	3	3	4	3
Cost	10	Cost per m3 (CAPEX)	5,0%	4	1	5	4	1	4	1
		Cost per m3 (OPEX)	5,0%	2	4	3	2	3	2	4
			SCORE:	3,0	3,7	4,1	2,2	2,3	3,0	3,0

Figure 26: MCA scores and results

7.2.1 Carbon footprint and Sustainability

- *Energy consumption* $[MJ/m^3]$: The fully-autonomous submerged dredger (FASD) is operating very close to the bottom of the canal and therefore it does not require a long suction pipe to lift the sediments. Furthermore the transportation is happening underwater, making this concept to require only 7 MJ/m^3. For these reasons this is the most energy efficient concept among the others. Given the considerable amount of pipelines needed for the poolbuoy (PB) concept to work, this method has scored the lowest as its energy consumption even exceeds the one of the conventional hopper dredger (TSHD).

- *Emissions during construction*: The emissions depend heavily on the type and quantity of materials which the device is made of. It is noticeable that the permanent structures are the ones that scored bad here, the floatable rugs (FR) emissions are extremely high because of the huge amount of plastic needed to build them in order to cover the entire area. On the other hand, the sloped water injection dredger (SWID) is the winner with only 450 tons of CO2 emitted for the construction, that is because the vessel is small and the only task it has to do is inject water in the soil. Therefore, less machinery is needed onboard.

- *Environmental impact*: The environmental impacts are assessed on the impact on sea-life and the possible leakages that can occur during the process. The SWID again performs better than the other methods. This is because this method is only blowing the sediments into a sediment trap so it has a minor impact compared to other methods that sucks everything from the bottom. The shark teeth trailer (STT) is also performing well given the fact that these trailers are just shoveling mud at low speed.

7.2.2 Interference, Risk & Safety

- *Interference with traffic*: the FASD is scoring the highest for this criteria, this is the result of the fact that it is operating underwater and therefore most of the ships can sail above. On top of that, the transportation is also fully underwater, instead of relying on a barge like most of the concepts. The FR is the concept with the biggest interference because when the rugs are lifted they reach the surface causing disturbance with maritime traffic.

- *Human threats*: This criteria like the previous one is hard to quantify. The SWID has the lowest risks for humans, as its relatively easy to carry out any maintenance duty and the construction/maintenance of the vessel does not involve any threats for humans. The concepts with the biggest risks are the ones that requires people to go underwater periodically eg. STT and FR.

- *Level of Autonomy*: Concepts that are fully autonomous scored higher on this one: FASD, STT, FR and PB have a score of 4. Manned supervised operations scored lower: SWID, H2indenburg with a score of 1.

7.2.3 Reliability

- *Robustness*: Because of the little amount of moving parts the SWID scored high in this category. A hopper dredger for example has a higher risk on hitting material that is too hard or large to suck up. The FR scored the lowest as there is a big risk on sediment ending up under the rugs. On top of that, the rugs have a lot of moving parts that could fail and if they do, it is difficult to fix as everything lies 25 m below sea level. The PB also scored low, this is mainly due to the large length of the pipes system. The STT scored average because once it is built, the system is not very complicated.

- *Accessibility*: Due to the fact that the construction for these concepts is located on the bottom of the sea, the STT and the FR scored the lowest. The methods that use ships that are above water all the time, e.g. SWID, naturally score the highest.

- *Technology Readiness Level*: Because of the fact that the FASD requires an **underwater** autonomous navigation system, it scored the lowest. This technology has not been implemented yet anywhere in the dredging industry. The SWID and H2indenburg score higher than other concepts because they are relative conventional methods running on different energy carriers.

7.2.4 Cost

- *CAPEX*: Because of the large amount of required materials and the complexity of the structures, the solutions using a permanent underwater structure (FR and STT) score low on the CAPEX criteria. The small SWID vessel is relatively cheap resulting in a high score.

- *OPEX*: The operational cost are a product of the energy consumption, autonomy and robustness. Therefore, the relatively low energy consuming autonomous methods FASD and STT score the best. The non-autonomous H2indenburg requires crew and therfore has a higher operational costs and thus a lower score.

7.2.5 Final scores

From figure 26 it becomes clear that the SWID with a score of 4.14 is the winne, closely followed by the FASD, scoring a 4.12. Both are robust methods, the SWID scores better on costs but the FASD has a lower energy consumption. Then, despite their big design differences, follow the STT (3.04) and the H2-indenburg (2.97). Although the FR scores really well on energy consumption, it loses at costs and emission during construction, resulting in a score of 2.25. The PB ended last with a score of 2.17.

7.3 Sensitivity analysis: other scenarios applied to the MCA

The initial weighing of the criteria has been done from the research case point of view. In this weighing the carbon footprint and sustainability category was the most important factor in determining the outcome of the MCA. In this section will be demonstrated how the outcome of the MCA looks like if different scenarios would be used to divide the weights to the categories. The other scenarios are the business case, the always function case and the NINA case.

7.3.1 The Business Case

The business case is a scenario where the weights would shift from the environmental category towards the cost category. A division of 5%, 25%, 25%, 45% can be given to the categories respectively. This is a scenario which might lie closer to the demands of a listed company like Boskalis. The results of this scenario can be seen in the appendix (figure 28). The winners of this scenario are the SWID followed by the FASD. The SWID is a winner in this scenario because the initial investment, employee salary and energy consumption are most affordable compared to the other concept work methods. From this scenario can be concluded that the initial investments of the permanent structures are too expensive to be dissolved by their advantages.

When comparing the SWID to the conventional Hopper Dredgers, it looks like SWID could be a more cost efficient competitor than the hoppers. The use of permanent structures at fixed locations connected to the grid will save money in salary and fuel costs.

7.3.2 The Always Function Case

The always function case is a scenario where the reliability of the concepts is the most important factor in the MCA. If Boskalis accepted any kind of investment in such an expensive project to reduce emissions, it sure would want it to be a watertight solution. The weight could be distributed in such a way that reliability plays a big role followed by interference, risk & safety. A division of 5%, 30%, 50%, 15% can be given to the categories respectively. Additionally one might argue the role of the TRL criteria in the reliability category. Some concepts still have technical hick-ups from which is assumed they will be solved in the future. The results of this scenario can be seen in the appendix (figure 29). The winners of this scenario are the SWID followed by the FASD and the H2indenburg. The work method involving SWID is a winner in this scenario because it uses proven technology. Fixed structures like punaise pumps have proven themselves in past operations and the water injection dredging technology has proven to be effective in multiple field tests in the port of Rotterdam.

The FASD and H2indenburg compete for second place in the scenario. When taking into account the risks for submerged vessels in the harbour and regulations involved with them, the hydrogen powered hopper is the second best solution. The technology for hydrogen has been proven to be feasible to fuel ships. The possible hydrogen hub in the port of Rotterdam makes this concept also really attractive for this region.

7.3.3 The NINA case

The No Injuries No Accidents Case is a scenario where the interference, risk and safety is prioritized. This is closely followed b reliability on second place to minimize maintenance works. This scenario is generated from the point of view of the Port of Rotterdam. They might prefer a solution with the least amount of interference to ensure safe accessibility of the entire harbour. A division of 5%, 40%, 40%, 15% can be given to the categories respectively. Additionally, the categories for interference, risk & safety and reliability could be expanded by adding a more extensive risk assessment for all the concepts. Due to time restrictions a full risk assessment could not be performed.

The results of this scenario can be seen in the appendix (figure 30). The winners of this scenario are the SWID followed by the FASD and the H2indenburg. THe SWID and the FASD both have great manoeuvrability to prevent them from colliding with other vessels in the Maasmond. The H2indenburg, in the sense of manouvrability, is very similar to conventional hoppers. The Poolbuoy is more restricted in its movement and the Floatable Rugs occasionally prevent the accessibility.

7.3.4 Isolated Category Testing

Additionally to the other scenarios, the MCA has also been run four times granting the full weight to one category each time. By splitting the MCA into four isolated categories, it can be seen if some categories might be more favourable to some concept work methods. When performing this test, it can be concluded that the SWID and the FASD still end up top in most of the cases. When granting 100% to the reliability category or the cost category, the H2indenburg takes second place in the outcome. This will be taken into consideration, for there are certain countries that care less about the environment and safety in general. A problem involved with this is that these countries usually do not have much hydrogen fuel widely available.

7.3.5 Bias test

A bias test has been performed in order to check whether the scores given were somehow biased. This test consisted in narrowing the range from 1-5 into a smaller range of 2-4 only, so basically every 5 became a 4 and every 1 became 2.

At first the outcome (ranking) did not change, the SWID and the FASD are still dominating and the scores were just closer to each other. However if a full focus on single category is applied, for example Carbon footprint and Sustainability category get 100% then the concepts making use of permanent structures like the STT and FR get a big boost on their total score, this meets the expectations as one of their strengths lies in a lower energy consumption during operation. When Reliability is on focus, the H2indeburg takes the lead as the work method is close to the traditional hopper dredger which is already reliable and widely applied.

7.3.6 Sensitivity Analysis: Conclusion

By applying different weights to the MCA, it can be concluded that the SWID and the FASD are always the winners. This shows that the outcome of this MCA is resilient to different scenarios. Therefore, it can be concluded that by using this set of criteria, two solutions come out best.

8 Iterations

From chapter 7 conclusions can be drawn for every concept on which aspects they score better or worse. In this chapter the weaknesses and strength are highlighted, later this knowledge is used to address some improvements on the concepts.

8.1 Weak and strong points of each concept

In order to further improve concepts and to see if concepts can be combined, this section will point out the weaknesses and strong points of each section.

8.1.1 Fully autonomous submerged dredger

The FASD scores high in a lot of categories. It has the lowest energy consumption of all concepts, this is because of the fact that the sediment is not pumped up to the surface level. The submerged aspect of the FASD also makes the interference with traffic low. The autonomy results in low OPEX and higher safety. The weak points are the fact that no extensive testing has been done with FASD technology. Another risk is that if the propulsion mechanism fails the FASD becomes hard to acces as it is on the bottom of the ocean. To solve this problem, an emergency floating system could be installed.

8.1.2 Sloped water injection dredger

The best performing concept is a result of its robustness, its safety, its costs and its low emissions during construction. The latter two have to do with the fact that it is a relatively small ship, resulting in a low amount of material. It scores not very high on the energy consumption, which is a result of the fact that the sediment still needs to be pumped up and transported over the water. This shows possible improvements like transporting the sediment underwater. The present crew also drives up the OPEX, an autonomous solution should be explored.

8.1.3 Poolbuoy

The bad result of the PB is mainly a result of the large required piping system. This makes the system high in energy consumption, not robust and costly. The main lesson that should be drawn from this concept is that large piping systems should be avoided.

8.1.4 Floatable rugs

Although performing very well on the energy consumption, the large amount of required material drives the MCA - scores for emission during construction and costs down. Because of its low energy consumption this concept should not be disregarded fully as it possibly could be a part of a combination of concepts. An option that could be explored is a combination with SWID where the sand is collected in a sediment trap that is kept empty using FR.

8.1.5 H2-indenburg

Although not scoring very high on energy consumption, the H2-indenburg compensates in other categories like robustness. This is because it is using known techniques used in hopper dredgers. Furthermore, this method is flexible since it is sailing on top of the water. Most importantly, this concept did proof that running on hydrogen is definitely an option for emission free maintenance dredging.

8.1.6 Shark-teeth trailer

The STT is efficient in its energy usage during operation. Also due to the fact that once built, the operation is relatively simple. Drawbacks are related to the fact that the concept uses a lot of material, this causes high emission during construction and high CAPEX. The fact that its permanently submerged makes it also difficult to reach for maintenance and requires a real sturdy material.

8.2 Improvements

After highlighting the weaknesses of each concept, this section will discuss possible ways to overcome the issues that come along with each concept.

8.2.1 Submerged transportation

The majority of the energy used to complete the dredging process is during the transportation. Minimizing the energy in this sub-process significantly improves the total efficiency. It can be seen that the FASD scores high on the energy consumption, mostly because it is submerged. Submerged vessels experience little drag, due to minimal wave breaking resistance and wave generating resistance. As the total wave resistance can account for almost 50% of the total resistance, being submerged significantly improves the total efficiency. Another great part of the total energy consumption is used during the pumping of the sediment over a height of 25 meters, by being close to the seabed this is also overcome. For these reasons a submerged transportation vessel could be a great benefit. Again the loading of the submerged barge is an issue, which can be solved by using stabilization legs during loading.

Calculations show that the total required energy per cubic meter for a submerged barge is only 2.9 MJ/m^3. To compare this to the conventional transportation barge we consider a vessel with a capacity of 935m^3, a sailing speed of 7 knots and a drag coefficient of 0.3. This drag coefficient is in the range of sub-optimal shapes which will likely suit the shape of the submerged barge. For reference a sphere has a drag coefficient of 0.47, which is not an optimal shape.

8.2.2 Shark-teeth trailer without rails

The use of fixed structures is very helpful in lowering the energy consumption of the overall process, however the placement of an underwater rail system poses many challenges that make the whole concept less feasible especially if costs and the emissions to produce them is of importance. One possible way to get rid of this big amount of steel needed would be the use of a tugboat coupled with a large tank with slides that can reach to the bottom and plough the sediments to the desired collection point. The capacity of the tank can be increased from 200 m^3 to 800 m^3 while the original design of the tank can still be used. The boat can proceed slowly around 1.5 kts (0.77 m/s) in order to reduce the drag force resistance generated by the mud, by doing so the boat is also able to complete several rides over the same time-span of the original concept based on tidal cycles that was constrained to a limited speed of 0.1 m/s because of the low tidal current at the bottom. The boat can also be helped by the tidal currents at the water level.

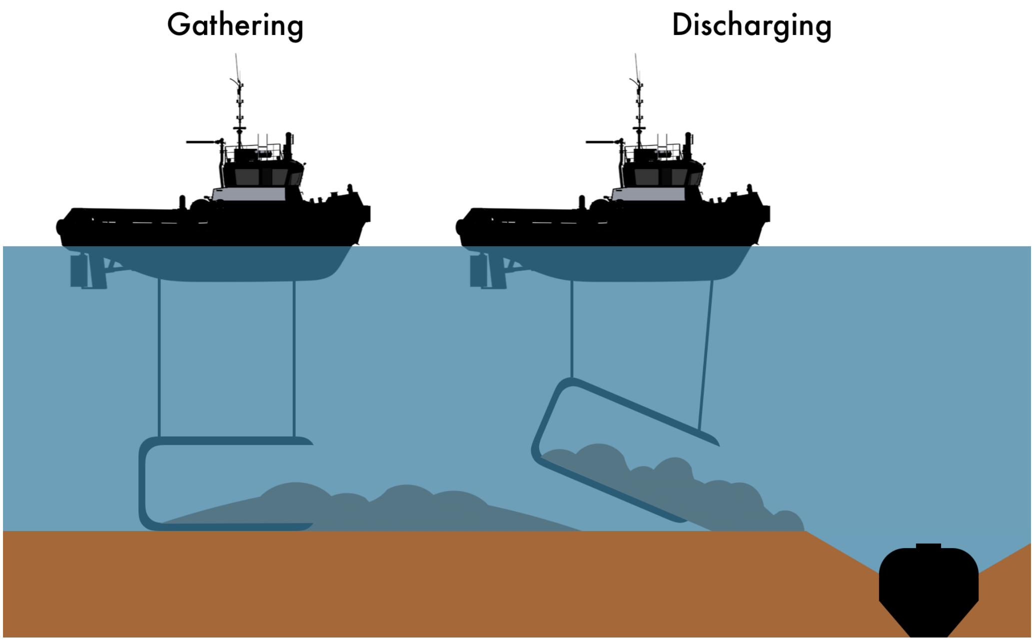


Figure 27: Visualization of improved shark teeth trailer working principle

Since this is a big alteration to the original concept, it is required to re-estimate the overall energy consumption of the collection process. Getting rid of the rails and making the tank to slide directly in contact with the bottom of the canal translates into higher friction with the ground. The kinetic friction coefficient has been assumed to be μ_k=0.3, though experimental tests are needed for an accurate value. New energy consumption for collection is therefore estimated by solely accounting for the summation of the drag force (dependant on the speed) and the friction force with the ground. The propulsion of the tug vessel is assumed to be similar to the one of a water injection dredger but the size can be even reduced, as the equipment on the ship would be minimal and most of the space will be occupied by the fuel. The new total energy consumption of the process is estimated to be:

$$E_{collection} \approx 6.23 - 8\text{MJ}/m^3 \tag{10}$$

$$E_{tot} = E_{collection} + E_{pumping} + E_{transportation} \approx 18\text{MJ}/m^3 \tag{11}$$

As expected, it can be argued that the energy consumption compared to the original concept more than doubled, however the lower CAPEX, lower emissions during construction, less human threats and better accessibility make up for the big increase in the energy consumption.

The tugboat can possibly be powered using hydrogen, since Port of Rotterdam is currently trying to expand its hydrogen production. The equipment required onboard is minimal since the only scope of the boat is to drag the tank, most of the space can then be reserved to store the fuel. Considering the very short operational distance that the tugboat has to travel within the Port the size of the hydrogen tank is expected to be somewhere between 10 - 12 m^3.

9 Conclusion

A comprehensive research was performed regarding emission free maintenance dredging in a harbour environment. Several new fully working concept work methods were designed on paper. The concepts were designed in such a way that they covered a broad spectrum of solutions with respect to the final goal. This way the later performed multi-criteria analysis (MCA) gives a valuable insight in the strengths and weaknesses of each concept. These takeaways are finally implemented in the iterations to see if this improves the concepts or not.

Firstly, it is shown that directly implementing a green energy carrier, like hydrogen, methanol or batteries, in the convention trailing suction hopper dredger (TSHD) is not possible. The energy density is too low and thus the volume of these energy carriers too large. It can be concluded that a harbour environment is an excellent location to perform emission free maintenance dredging. The distance that has to be traveled is limited and energy sources are always nearby. This facilitates a lot of opportunities for new concept work methods.

For this new concept work method to be emission free, we consider three incentives:

1. **Improving the overall efficiency**, by improving the overall efficiency the total used energy decreases enabling the use of a green energy carrier.
2. **Making use of a more frequent process**, by using a more frequent process the amount of to-be-dredged sediment decreases for each trip and thus makes the use of a green energy carrier possible.
3. **Splitting up the entire process**, by doing this the sub-processes that are created all require less energy. The total process is split up in three sub-processes. (i) The gathering of the sediment to a central location, (ii) the pumping of the sediment from the bottom of the harbour to the water level, (iii) the transportation of the sediment to the dumping area.

Especially this last incentives gives a lot of great advantages and opportunities. (i) Each device for every sub-process can be designed to be tasks specific, increasing the efficiency. (ii) As the total process is split up, every sub-process requires less energy and thus less installed power. (iii) Some of the sub-processes can make use of fixed structures. The fixed-structures are static and can therefore be directly connected to the electricity grid. This way, an energy carrier is omitted completely.

In this research six different concepts have been designed, elaborated and tested by the means of a multi-criteria analysis followed by a sensitivity test at a later stage. From this analysis, where costs of the total project are considered to a lesser extend, two concepts can be pointed out to be the winners:

- **Sloped Water Injection Dredging** (SWID), This concepts looks very promising as it is very robust, fairly cheap and is a proven technique in the Port of Rotterdam. Future research should be done regarding the currents at the dredging location. The currents could interfere and thus decreasing the efficiency of the total process, but could also be used in its advantage. As the Port of Rotterdam plans to implement a vast hydrogen energy network across the harbour and this concept runs on hydrogen, both parties could greatly benefit.
- **Fully Autonomous Submerged Dredger** (FASD), this concept looks promising for a later stadium. Apart from some other issues, the lowest overall energy consumption and minimal interference with the traffic makes this concept score high on the MCA. It is also worth to mention that this concept is the only concept that covers the entire process, and can therefore easily be applied in different location.

Some other overall conclusions that can be drawn from the MCA: in the six initial concept work methods, two concepts with vast permanent underwater gathering structure were considered. The methods tend to have a low energy consumption, but as they are very material intensive, have a high level of maintenance and are very expensive, they still score low on the MCA. Other concepts that make use of complex and long piping systems to collect the sediment at a central location also score low on the MCA as the energy losses are simply too high.

Contrary, keeping the sediment close to the bottom of the harbour when dredging improves the efficiency. Making use of a fixed pump also helps to achieve the zero emission goal. Finally, it is shown that the transportation requires the majority of the total energy. Within this process the most energy can be won. When making use of simple split barges they can run on battery-packs, but when making use of the free local energy they can perform even better. Fitting the barges for instance with sails may improve the efficiency even more.

When looking once more at the research question:

"Design a cost efficient emission free concept work method for maintenance dredging works in a harbour environment for recurring yearly cycle."

It can be concluded that it can definitely be done. With the current technology is should be doable to perform maintenance dredging in a harbour like environment. And when considering the future research in different technologies it looks even more promising.

10 Recommendations

This section contains the recommendation for students to perform extra research on topics when investigating emission free dredging. The recommendations are ordered into different categories.

Alternative Fuels
Having performed this project and researching the possibilities of alternative fuels, the opportunities to replace diesel seem very attractive. Particularly hydrogen is very promising. It cannot be stressed enough that further research and implementation of this technique should be encouraged. The leading companies in the energy industry should be the first to take a leap in a new direction. This will set an example for countries and other businesses and set of a chain reaction into an environmentally friendly way of using energy.

Energy reduction
Secondly, one of the most feasible ways to reduce emissions is to increase efficiency. This can be done by making sure that as few energy as possible is wasted and that free energy such as wind, solar and tidal energy is utilized to its full potential. The research into energy reduction for marine traffic has an insane amount of potential. Energy reduction for propulsion for the barges is a simple and reachable goal to strive for. The use of aerofoils is becoming a more and more common technique to use. The suitability for these techniques in country infamous for windy conditions should be exploited. Together with MARIN, a Dutch marine research institute, research could be performed. Companies should be able to see the financial benefit of using these developments when designing new vessels.

The solar energy in the Netherlands in not as powerful as in other parts of the world. Therefore, it might not be successful in the harbour of Rotterdam. In other parts of the world, a large floating solar panel could be used to supply energy to electric hopper dredgers or electric cutter suction dredgers.

For the harbour of Rotterdam, the use of tidal energy from the North Sea and current energy from the Dutch rivers is a valuable source of energy. The flow of water contains a high density of energy and besides that, is a very predictable energy source. Retrieving this energy is a difficult job and is currently researched at institutions like TU Delft. Wave Energy Converters (WEC's) can play an important role in the future of dredging for most of the dredging activities operate at sea. The By extracting energy from waves, the reduction of emissions can be accelerated. Electric dredging vessels equipped with a WEC might be the solution Boskalis is looking for the reach their ambitious goals of being carbon-neutral in 2050.

Dredging Methods
This report contains some concepts that are more controversial then others. The poolbuoy concept for example. The concept had to be altered in a way to make it fit for an operation of this size. In the end, it was not able to outperform other concepts. A suggestion for further research is to see if a completely autonomous underwater robot can perform the maintenance. A combination between the poolbuoy and the FASD concept might be the perfect solution. It would have the benefits of being submerged and autonomous. For this project, complex underwater robots have been left out of the possible concepts on purpose. Research into this subject might result in promising solutions for Boskalis.

Stakeholders
Some of the concepts analysed in this report make use of permanent structures, and since the normal contract for maintenance works has a time span of five years, more regulations are needed between the different stakeholders involved: Port of Rotterdam - Boskalis - Rijkswaterstaat.
The stipulation of a new agreement could bring new solutions, for example a longer contract time span that can increase the feasibility and investments in such fixed structures. Depending on the work method chosen, maritime traffic inside the Maasmond could be adjusted in future to account for the presence of dredgers and other auxiliary structures during service. The government/Rijkswaterstaat could also help making emission free options more economically viable by subsidizing green operations (even) more.

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Appendix

MCA sensitivity test results

Tables showing the results of the alternative scenarios for the MCA.

Business Case: Focus on cost efficiency

			CONCEPTS						
			TSHD	FASD	SWID	PB	FR	H2	STT
Category	Weight (%)	Abbreviation	score	score	score	score	score	score	score
Carbon footprint, Sustainability	10	CS1	2	5	3	1	4	2	4
		CS2	3	4	5	3	1	3	2
		CS3	1	2	4	2	3	2	4
Interference, Risk & Safety	25	IRS1	3	5	4	2	2	3	4
		IRS2	3	4	5	3	2	3	2
		IRS3	1	4	1	4	4	1	4
Reliabilty	25	R1	4	4	5	2	1	4	3
		R2	5	3	5	2	1	5	1
		R3	5	2	4	3	3	4	3
Cost	40	C1	4	3	5	4	1	4	1
		C2	2	4	3	2	3	2	4
		TOTAL SCORE	3,2	3,85	4,23	2,56	1,95	3,18	2,77

Figure 28: *Business Case: SWID and FASD clear winners*

Reliability Case: Focus on robustness of the concepts

			CONCEPTS						
			TSHD	FASD	SWID	PB	FR	H2	STT
Category	Weight (%)	Abbreviation	score	score	score	score	score	score	score
Carbon footprint Sustainability	0	CS1	2	5	3	1	4	2	4
		CS2	3	4	5	3	1	3	2
		CS3	1	2	4	2	3	2	4
Interference, Risk & Safety	0	IRS1	3	5	4	2	2	3	4
		IRS2	3	4	5	3	2	3	2
		IRS3	1	4	1	4	4	1	4
Reliabilty	100	R1	4	4	5	2	1	4	3
		R2	5	3	5	2	1	5	1
		R3	5	2	4	3	3	4	3
Cost	0	C1	4	3	5	4	1	4	1
		C2	2	4	3	2	3	2	4
		TOTAL SCORE	4,3	3,60	4,90	2,10	1,20	4,20	2,60

Figure 29: *Reliability case: SWID and H2 winners*

NINA - No Injuries No Accidents: Focus on Interference, human threats and reliability

			CONCEPTS						
			TSHD	FASD	SWID	PB	FR	H2	STT
Category	Weight (%)	Abbreviation	score	score	score	score	score	score	score
Carbon footprint Sustainability	5	CS1	2	5	3	1	4	2	4
		CS2	3	4	5	3	1	3	2
		CS3	1	2	4	2	3	2	4
Interference, Risk & Safety	40	IRS1	3	4	4	2	2	3	4
		IRS2	3	4	5	3	2	3	2
		IRS3	1	4	1	4	4	1	4
Reliabilty	40	R1	4	4	5	2	1	4	3
		R2	5	3	5	2	1	5	1
		R3	5	2	4	3	3	4	3
Cost	15	C1	4	2	5	4	1	4	1
		C2	2	4	3	2	3	2	4
		TOTAL SCORE	3,40	3,71	4,40	2,44	1,81	3,37	2,83

Figure 30: *NINA Case: FASD, SWID and H2 winners*

A more detailed estimate of the OPEX

OPEX estimates

Information supplied by Hilbrand and Sebastian

Normal hopper: €50.000/day
Loading capacity: 2400m^3
Time for one trip: 3.5h
Total m^3/day: 16.800 m^3
Diesel = 16.800/3 = 5600 L diesel ≈ €7000.-
Total cost maintenance ≈ € 3 / m^3

Boskalis Equipment Sheet of the Strandway shows

Loading capacity: 4.500m^3
Total m^3/day: 24.000 m^3
Diesel = 24.000/3 = 8000 L diesel ≈ €10.000,-
Total cost maintenance ≈ €2,4 / m^3

Information supplied by Cees van Rhee.

Usually maintenance contracts pay ≈ €1/m^3

According to this information Boskalis loses money.
So the question arises who is wrong?

If a normal hopper costs €50.000. What division can be made on the costs?

- ± €10.000 fuel
- ± € 10.000 crew
- ± € 30.000 maintenance/ship

Estimated price of H2

1kg = €5 = 120MJ [1] → 24 MJ/€ , compared to diesel which is ≈ 37 MJ/€

Fuel costs H2:

SWID:	13 MJ/m^3	= €0.54/m^3
FASD:	7 MJ/m^3	= €0.29/m^3
H2:	15 MJ/m^3	= €0.625/m^3
STT:	18 MJ/m^3	= €0.75/m^3

Fuel costs electricity[23] ≈ 20 MJ/€

SWID:	13 MJ/m^3	= €0.65/m^3
FASD:	7 MJ/m^3	= €0.35/m^3
H2:	15 MJ/m^3	= €0.75/m^3
STT:	18 MJ/m^3	= €0.90/m^3

Crew cost estimates per concept

SWID:	3-4 crew	= € 7.500
FASD:	1 supervisor	= € 2.500
H2:	5-6 crew	= € 10.000
STT:	2-3 crew	= € 5.000

Maintenance costs per concept (also compared to hopper)

SWID:	= € 10.000
FASD:	= € 5.000
H2:	= € 20.000
STT:	= € 5.000

Total OPEX costs per day: (on base of 13.000 m^3/day)

SWID: = € 10.000 + 13.000*0.54 + 7.500
= € 24.520 ≈ €25.000

FASD: = € 5.000 + 13.000*0.29 + 5.000
= € 13.770 ≈ €15.000

H2: = € 20.000 + 13.000*0.625 +
10.000 = € 38.125 ≈ €35.000

STT: = € 5.000 + 13.000*0.75 + 5.000
= € 19.750 ≈ €20.000

Figure 31: OPEX estimates

EMISSION FREE MAINTENANCE DREDGING

At the Port of Rotterdam

Boskalis

TU Delft

Pieter Kingma
Floris van Ingen
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Under the supervision of:

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Prof. Dr. Ir. Cees van Rhee (TU Delft)
Dr. Ir. Martine Rutten (TU Delft)

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IN THIS MEMO YOU FIND

Four ways of performing emission free maintenance dredging in the Port of Rotterdam. Each option also includes the necessary steps to take to make emission free dredging reality.

EMISSION FREE OPTIONS:

As part of Boskalis mission to become emission free by 2050, four TU Delft students were recruited to perform a 10 week research with the aim of providing the company with an overview of possible emission free methods forfor a yearly cycle of maintenance dredging in fixed areas. These methods were developed, on paper, for the entrance to the Port of Rotterdam. This memo presents an overview of the designed methods and will show you that emission free maintenance dredging is very much within reach! Readers interested in more background are advised to read through the accompanying slide deck and report.

There are three ways of making dredging emission free:

- Compensate emissions by carbon capture.
- Run operations on sustainable energy carriers (dynamic).
- Connect (parts of) the operation to the electricity grid (static).

This research focused on the latter two as those are options where innovation in the work concept method can be made.

SPLITTING UP THE WORK METHOD

An important part of the solution to get to emission free maintenance dredging is to split up the work method into three parts:

- **Collection** of sediment
- **Excavation** of sediment
- **Transportation** of sediment

In this way, each part of the solution can be designed for its specific task, kept small and becomes more energy efficient. The latter two enable the use of the often heavy or bulky green energy carriers. Splitting up the work method also enables the possibility to connect parts that can be static to the electricity grid.

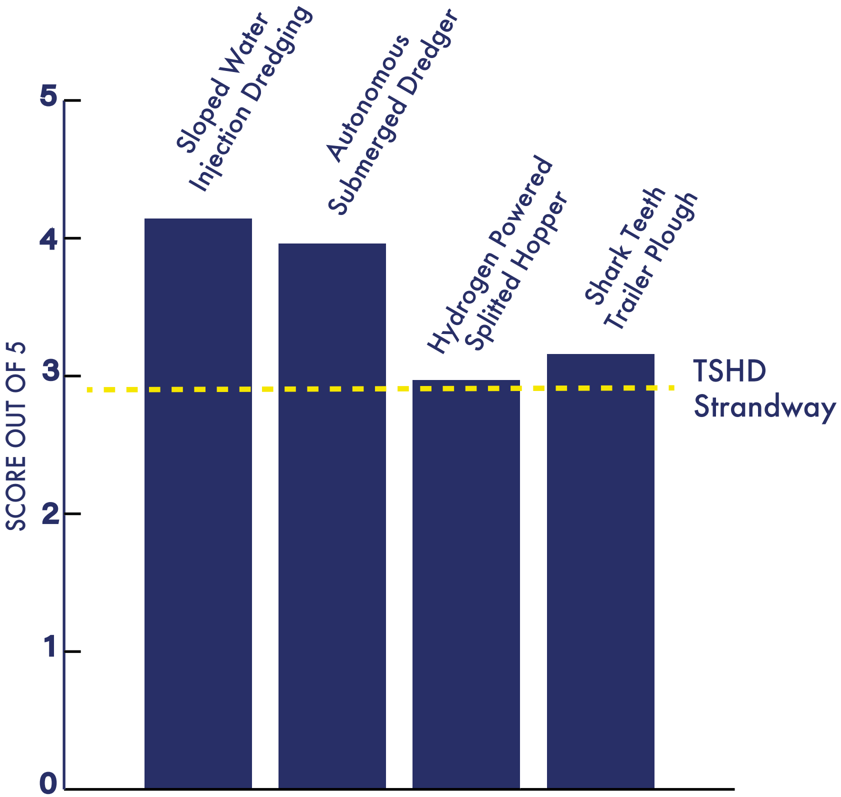
Multiple concepts were developed, all emission free and each handling one or multiple of the three mentioned dredging tasks (collection/excavation/transportation). They were ranked by means of a Multi Criteria Analysis (MCA). The best performing concepts are presented in this memo.

MULTI CRITERIA ANALYSIS

For the MCA, four categories were considered

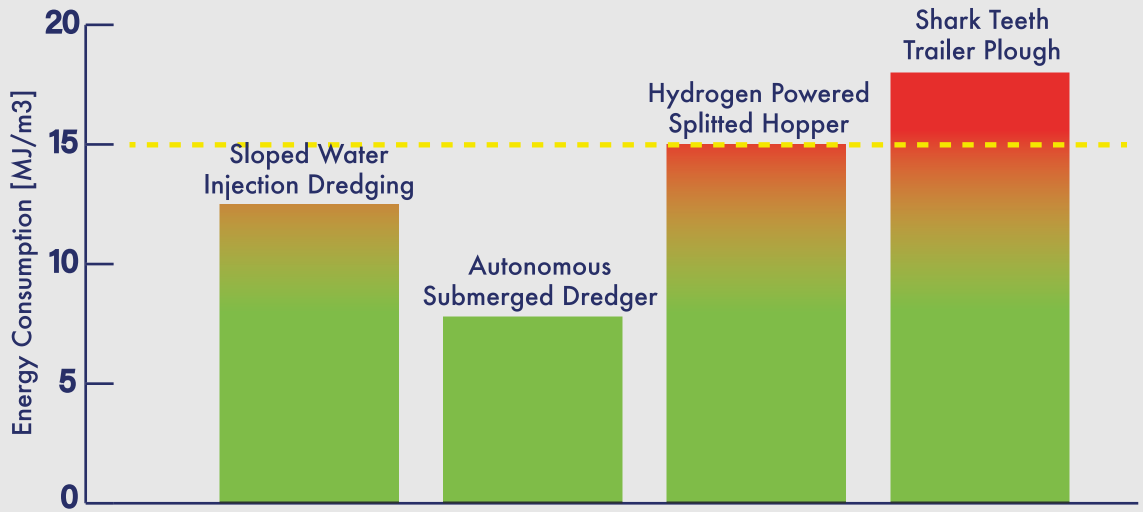
1.	Sustainability	40 %
2.	Interference, Risk & Safety	25 %
3.	Reliability	25 %
4.	Cost	10 %

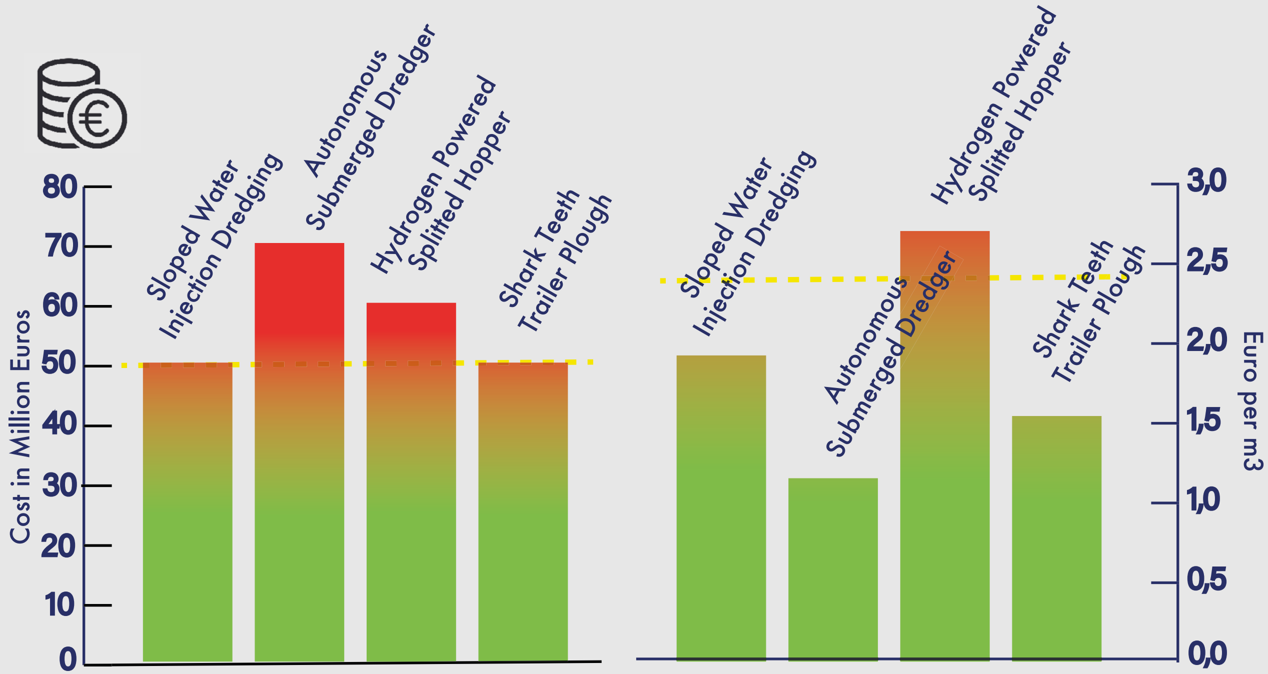
This page presents a summary of the results of the best scoring concepts. The reader is referred to the report for more detail.



MULTI CRITERIA ANALYSES FINAL SCORES

ESTIMATED ENERGY CONSUMPTION OF DREDGING METHOD





CAPEX **OPEX**

OVERALL TAKEAWAYS

DO

Split up the process

- Designs become task specific and thus more efficient.
- Less required power enables green energy carriers.
- Oppurtunity to use fixed structures connected to the grid.

Keep the sediment submerged

By not lifting the sediment to the surface, a lot of energy is saved.

Use Hydrogen in Port of Rotterdam

The Port of Rotterdam aims to have introduced a large scale integrated hydrogen network across the Port by 2030. Jumping in on this trend can be very fruitful for both parties.

DON'T

Transport through complex pipelines

When using long and complex pipelines or hoses, a lot of energy is lost due to friction.

Use large permanent underwater structures

A design that did not pass the MCA test, consisted of a large ploughing system on rails. Although energy consumption of such methods is low, they are way too material intensive.

SLOPED WATER INJECTION DREDGING

Use water injection dredging combined with sediment traps to COLLECT the sediment in central locations. EXCAVATE the sediment traps continuously using static pumps.

Water injection dredging (WID) puts settled sediment back into suspension by injecting it with water under high pressure. The water with the suspended sediment is heavier than its surrounding water and therefore moves downhill, getting underneath the lighter water. At the site, multiple permanent pumps are placed at the bottom of the harbour that create downhill conical shaped sediment traps. These pumps are connected to the electricity grid. Following an outward rotating path starting at the pump, a hydrogen powered WID vessel puts the sediment in suspension. If there are no currents interfering, the water with the suspended sediment will end up at the lowest point of the slope: the sediment trap. From there, barges are filled that take care of transportation.

- **Emission free**
- **Case study: OPEX reduction of up to 40 %**
- **Case study: no maintenance for 2 months**
- **Small and maneuverable vessel: low interference**
- **Energy usage is approx. 10 - 15 MJ/m3 (TSHD uses 15 MJ/m3)**

Current Stage

- Diesel powered
- TSHD empties sediment trap

Research

- Next-gen WID vessels on hydrogen
- Modelling sediment transport after injection
- Currents at project site

Costs

- 2 WID vessels: 20 M
- 5 Barges: 10 M
- 10 Pumps: 10 M
- **Total: 40 M**
- **OPEX:** 1.92 euro/m3

Operational

- WID running on hydrogen
- Fixed structures connected to grid
- Within 5 years

AUTONOMOUS SUBMERGED DREDGER

Similar to a robotic vacuum cleaner, this vessel maneuvers autonomously over the bottom of the harbour. It EXCAVATES and TRANSPORTS the sediment remaining submerged.

By performing the dredging of the sediment underwater, the sediment is not lifted to the surface. This saves a lot of energy. The entire process uses half of the energy a hopper dredger would use. The submerged dredger runs on a 10 m3 battery pack, providing 3000 kWh. The fact that it is autonomous eliminates the cost of crew. Autonomy also allows for charging when green energy is available. The bouyancy of the submerged dredger is ensured using air chambers. Stability is ensured by placing stabilizers on the seabed floor during loading.

- **Emission free**
- **Energy usage is 7 MJ/m3 (half of TSHD)**
- **Little interference with traffic**
- **No need for permanent structures**
- **Low OPEX**

Source: C-job

Research

- Underwater navigation software
- Autonomy regulations should change
- Test and overcome possible bouyancy and stability issues during loading
- Charging station connected to smart-grid

Operational

- Multiple small vessels
- Powered by batteries
- Low energy usage
- Low interference with traffic
- > 10 years

Current Stage

- Preliminary design on paper (C-job)
- Technology for autonomous vehicles available

Costs

- 3 Submerged dredgers: 60 M
- 1 Charging system: 10 M
- **Total: ± 70 M**
- **OPEX:** 1.15 euro/m3

HYDROGEN POWERED SPLITTED HOPPER

Splitting the hopper dredger into a separate DREDGING and TRANSPORTING vessel enables the use of hydrogen as energy carrier in the Port of Rotterdam.

The Port of Rotterdam has the goal of becoming the world's number one hydrogen hub. By 2030, a port wide hydrogen network providing green hydrogen should be in place. The downside of hydrogenis that its energy density is low, which means a lot of volume is needed to store the required energy. However, the required tank size is kept small by the facts that firstly, during maintenance dredging, travelled distances are small and secondly, liquified hydrogen will be widely available on site. The split of the hopper dredger into a dredging and transportation vessel also contributes to this.

- **Emission free**
- **Hydrogen tank of 5 - 10 m3**
- **Known and proven technique**
- **Maneuverable vessel: low interference**
- **No need for permanent structures**
- **Conveys with mission of Port of Rotterdam**

Current Stage

- Hopper dredger running on diesel
- No split of activities
- Port of Rotterdam aimes to become world leader in Hydrogen

Research

- Wait for hydrogen developments in Port of Rotterdam
- Increase efficiency of Hydrogen production
- Design and create Hydrogen powered splitted hopper

Costs

- 1 Hydrogen system: 0.55 M
- 1 Vessel: 40 M
- 7 Barges: 14 M
- **Total: ± 55 M**
- **Opex:** 2.7 euro/m3

Operational

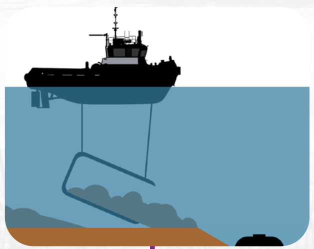
- Dredger powered by hydrogen
- Discharging into autonomous barges
- Within 5-10 years

SHARK TEETH TRAILER

Use a ploughing system that shovels over the bottom and COLLECTS the sediment at a central location from where it is EXCAVATED by a permanent pump. The used container leaves a trench behind that recalls a 'shark teeth' shape.

The ploughing technique is one of the oldest dredging techniques ever used ('Krabbelaar'), back then primarily used as bed levelers. The shark teeth trailer (STT) is a revised form of this method. It consists of a tug vessel powered with hydrogen or by batteries with underneath, a detachable container that scrapes over the seabed and stores the sediments until a pick-up site is reached. Here the sediments are released and pumped into an autonomous barge that will eventually dump the sediment elsewhere.

- **Emission free**
- **Very simple and thus robust**
- **Energy usage ±18 MJ/m3, more than TSHD**
- **Low in maintenance**



Research

- Design of container, find optimal shape
- Filling up process of the container
- Influence of Shark teeth shape on sedimentation
- The exact resistance of the sediment when dragging the container

Operational

- Tugboat powered by hydrogen or methanol
- Sediment is collected at central locations
- Fixed structures pump up sediment

Current Stage

- Not applied on this scale
- Preliminary design based on old harbour maintenance technique

Costs

- 2 Tug vessels: 20 M
- 2 Ploughing system: 4 M
- 8 Barges: 16 M
- 8 Pumps: 8 M
- **Total: ± 48 M**
- **OPEX:** 1.54 euro/m3

EXCAVATION

PERMANENT PUMPS

The great advantage of working with fixed dredger heads (pumps) is that these can be connected to the electricity grid. This enables the use of green energy that was harvested elsewhere.

The technique was used already in the 1990s in the form of the Punaise-pump. The Punaise was a semi permanent structure that was able to dredge with an energy usage of 5.4 MJ/m3. It operates from the bottom and is permanently submerged. During operation, a pit is formed around the Punaise, making it the lowest point in its surroundings. This 'draws' the sediment towards the Punaise. Back in the 90s the Punaise ran on fossil fuel but now it will be changed to run on electricity. Another alteration is that this time the pump is really permanent, attached to the seabed and not easily removable. This prevents problems related to storms. The pump will fill the autonomous barge that is described on the right.

TRANSPORTATION

AUTONOMOUS SPLIT BARGE

Autonomous barges run on batteries and can go whenever there is a surplus of green energy in the grid. The energy provided by the batteries can be complemented by sails. Another possibility to save energy is to fill and sail the barge underwater.

The transport of sediment has a big share in the energy consumption of the dredging industry. Some reports say that it adds up to 50 % of the energy consumption. In the case of the project site in the harbour of Rotterdam, 7.3 MJ/m3 is used for transporting the sediment to the dumpsite at 20 km. This is indeed half of the used energy. Split barges traveling should carry a battery pack of 4.4 m3 for one trip to perform this job emission free.

It is expected that in the near future transportation ships using wing sails will become available. This will bring the possibility of decreasing energy usage for transport by 80 - 90 % (Oceanbird is working on this). A technique that is already used more often is that of the flettner rotor sails. These can decrease energy usage by 8 - 25 %.

A final possibility is filling and sailing the autonomous split barges underwater. Although this technique might be a bit more complicated, filling and transporting the sediment underwater reduces energy usages significantly. The reasons for this are that the sediment no longer has to be pumped up to the surface and secondly that underwater sailing has almost no wave resistance. This can decrease energy usage of the process by more than 50 %.

HAPPY DREDGING **Cheers from fieldtrip Friday at the Maasmond**

Pieter Kingma
Floris van Ingen
Fabio Curzi
Jan Geleijnse