Sustainable sediment management in ports

The development of a decision-making approach applied on a case study of Porto Amboim

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TU Delft ARCADIS

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by

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to obtain the degree of Master of Science in Hydraulic Engineering

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Acknowledgment

This thesis marks the and of an era. Via a detour in Mechanical Engineering, I followed my passion for water and sand to Hydraulic Engineering. For the past nine months I have conducted this research for the TU Delft and Arcadis to complete my Master of Science in Hydraulic Engineering. During these different times of the pandemic, I mostly worked from my own room but still conducted interesting research. I enjoyed writing this thesis and learning more about sustainable sediment management. This report summaries all the findings of the research and I hope you enjoy reading it.

During this research, I have received a great deal of support and assistance from my graduation committee. They challenged me during the process and were always available for all my questions. I would like to thank them for their assistance and support in these past nine months.

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Enjoy reading this report.

Eva Elina Houbiers
Delft, June 2021

Abstract

Ports are located in deltas and dynamic coastal regions with large loads of fine sediment. Ports also enhance the import of marine sediment by channel and basin deepening. This results in the need for extensive maintenance and sediment management. Finding an effective and efficient sediment management strategy is difficult. This research dives into the current sediment management approaches and innovations to develop a decision-making approach to find the most suitable and sustainable sediment management strategy for a port.

There are several ways to optimize the sediment management in a port. With the principle to consider sediment as a value resource to the port and the coastal system, rather than a waste, the sediment management hierarchy is obtained. This hierarchy consists of Prevent and Reduce, Recycle and Reuse and Disposal to find a sustainable sediment management strategy. Various Prevent and Reduce and Recycle and Reuse examples and methods are analysed in this research to identify their potential for sustainable sediment management. Furthermore, based on literature study, expert interviews and a workshop at Arcadis input is generated to propose a decision-making approach. This research develops an approach and a tool considering all the aspects of sediment management and for assessing potential strategies for sediment management in a port.

The decision-making approach considers four steps to find a sediment management strategy. The first step, *sediment management objectives*, defines the objectives of the stakeholders for the strategy. In the second step, *fit to case*, all the sediment management methods are considered and the potential strategies are defined. The third step, *assessment of potential strategies*, assesses the performance of each strategy with performance indicators in the decision-making tool. The performance indicators are selected based on the assessment categories and objectives. In the final step, *meeting the objectives*, the most suitable strategy is proposed and described for the long-term sediment management in the port. This approach supports the process to optimize sediment management in a port.

The proposed decision-making approach is applied and further developed with a case study on Porto Amboim. Porto Amboim is a port on the west coast of Angola. The port operates for the offshore industry and is currently experiencing sedimentation problems. The northward directed natural longshore sediment transport is interrupted by the port's breakwater, resulting in sedimentation around the breakwater and at the lee side of the breakwater. This interruption disturbs the sediment balance in the region causing erosion problems at the down drift side of the port. The decision-making approach and tool are used to find a potential sediment management strategy for Porto Amboim. This potential strategy for Porto Amboim uses a sediment trap to manage the sediment in the region, ensuring sufficient port operations and restoring the sediment balance along the coast.

In order to use the approach in a generic way the results are reflected upon and a validation on the approach is performed. The reflection showed some uncertainties and limitations to the approach and tool because of the available information on the case. However, still two suitable strategies have been obtained for Porto Amboim. In the validation the approach has been applied on a second case study. This validation showed the potential for generic use of the decision-making approach and tool for sediment management. From the reflection and validation can be concluded that the available information determines the level of detail of the assessment of the potential strategies.

The main objective of this study was to explore the potential dredging and sediment management strategies to optimize sediment management in the port towards more sustainable methods, develop a decision-making tool and apply the tool in a specific case study. From this research the following can be concluded, the decision-making approach is considered a suitable approach to find a sediment management strategy for a port. All aspects of sediment management are considered and assessed. Therefore, further development of the tool and innovations in more aspects of sediment management are recommend. Yet, this research, the approach, and the innovative methods for sediment management show a great potential for more sustainable maintenance strategies in the future.

Contents

1
Introduction

"*Being more aware of the dynamic of sand moving past this coastline, even in times of no storms or swell, has proved to me that sand has its own life force, and it's incredible*"

Wayne 'Rabbit' Bartholomew, Tweed Sand Bypass advisory committee

1.1. Context

World trade is growing, and over 80% of global trade volume is transported overseas (PIANC, 2011). Coastal ports handle seaborne trade. These ports need to maintain navigable depth for efficient port operations. Many ports are located in deltas or regions with large loads of fine sediments. This results in many ports worldwide suffer from substantial volumes of maintenance dredging (Baptist et al., 2019). Ports also enhance the import of marine sediment by channel and basin deepening, worsening the siltation problems, resulting in the need for extensive maintenance and sediment management.

Maintaining the port's infrastructure area brings sustainability challenges. The increasing awareness for climate change asks for climate-adaptive management and solutions in port infrastructure and the dredging industry. Innovation is taking place to decrease the environmental impact of dredging vessels and maintenance dredging activities. Besides dredging, other sediment management methods are applied to optimize the sediment balance in the port area. These methods are interesting to use for climate-adaptive management.

These various dredging techniques and strategies are implemented all around the world, from standard dredging to innovative sedimentation reduction measures, such as sediment by-pass systems (Dyson et al. (2001)), sediment traps (Tempel (2019)), re-use of sediment or Building with Nature solutions (de Vriend et al. (2015)). A unique dredging strategy is set for each port to obtain an optimum between the required maintenance, lowest costs, port-specific aspects and environmental and social benefits. Choosing the right maintenance strategy for a port is a complex process because many different components influence this strategy; the design, environmental conditions, operations of the port, and (external) stakeholders.

Maintenance dredging in ports are a significant part of the port's yearly expenses. Optimizing maintenance dredging is interesting to reduce the maintenance cost for a port. As dredging is not the most sustainable measure, a reduction of required dredging also creates environmental benefits. Analysis and a good understanding of the coastal system give insight into the sediment transport patterns and sediment balance in the port area. Beneficially influencing these sediment transport patterns can decrease the siltation and positively influence the sediment balance.

The dynamics and uncertainties of the coastal system in which the port is situated, the different factors involved in port operations, and the need for innovation and more sustainable solutions ask for an overview and integrated framework to design the maintenance dredging strategy. This research dives into the current sediment management approaches and innovations to develop a decision-making approach to find the most suitable sediment management strategy for a port.

1.2. Problem statement and scope

Sediment management is an aspect that always needs to be considered in a port as inefficient sediment management results in inefficient port operations and higher maintenance costs. Optimizing the sediment management strategy for a port is a complex and challenging task. Many aspects are involved, and standard methods, tool or framework does not exist. To obtain a sustainable sediment management strategy for a port, all the important aspects need to be considered, and the challenges need to be taking into account. The main challenges of sediment management are:

- Cost and benefits
- Environmental factors
- Uncertainty in design and system response
- Varying stakeholder interests
- Maintenance techniques
- Long term benefits
- Extreme events

This thesis aims to create a decision-making approach to optimize the design and method of maintenance dredging and sediment management strategies for a port. The approach should lead the project team through all steps and decisions which are needed to obtain the best-fit strategy. To obtain the required strategy for the specific port project, all the factors for deriving the strategy should be involved in the approach. The resulting decision-making approach should contribute to process to the best-fit strategy and the preliminary design steps. In addition, alternative and innovative solutions and techniques should contribute to new strategies and alternatives in the maintenance dredging industry. This research focuses on the optimization of the sediment management strategies for existing ports.

The research scope will focus on three components, all contributing to the optimization of maintenance dredging and sediment management strategies for the port infrastructure and development projects.

1. Broad orientation to create an overview of the current state of maintenance dredging and sediment management.
2. A thorough investigation on specific dredging and sediment management technologies to find their potential to contribute to the optimization of the strategy.
3. The design of a decision-making support tool, a tool that contributes to the development of sediment management strategies for existing ports.

1.3. Research objectives

Following the problem definition, the main objective is determined. This is the main objective of the research and formulated as follows:

Main objective Explore potential dredging and sediment management strategies to optimize sediment management in the port towards more sustainable methods, develop a decision-making tool and apply the tool in a specific case study

To obtain this objective, the research is focused on the following five sub-objectives:

1. Map the current state of dredging techniques and strategies for port development projects and compare each technique's strengths, weaknesses, and opportunities.
2. Define the potential of various sediment management methods for sustainable sediment management strategies.
3. Create a decision-making approach and tool that provides insights into the different possible sediment management strategies, making it possible to choose the most suitable strategy for specific port development.
4. Perform a case study for an existing or newly developed port and develop a sediment management strategy for the specific case based on pre-selected performance indicators and reflect on the results.
5. Validate the decision-making approach and tool and assess the generic applicability of the decision-making approach.

1.4. Research approach

To obtain these objectives, the approach depicted in Figure 1.1 is followed. In the first part of the research, an extensive literature study, interviews, and a workshop at Arcadis gave insight into the current sediment management strategies and challenges and input for the decision-making approach and tool. In the second part of the research, a decision-making approach is proposed, and a tool is developed in Microsoft Excel. In the case study, the most suitable sediment management strategy for Porto Amboim is found by means of an assessment of seven different strategies. In the last part, the decision-making approach, tool, and results of the case study are reflected upon and validated, leading to the final results.

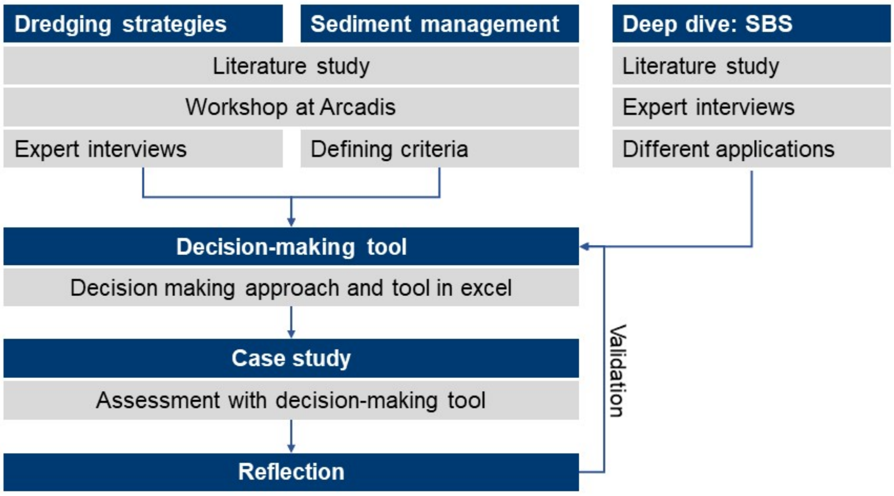


Figure 1.1: The research approach and methodology

1.5. Thesis outline

The research of this thesis is described in seven chapters, and the outline of this document is presented in Figure 1.2.

Chapter 2: Sediment management
This chapter focuses on the background information needed to understand the current sediment management methods in the port infrastructure and the potential for a different approach. A sediment management hierarchy is proposed.

Chapter 3: Decision-making approach
This chapter describes the decision-making approach to optimize the sediment management in the port and find the best-fit strategy. The steps of the approach are explained, and the application of the approach is described.

Chapter 4: Case study
The decision-making approach is applied in a case study and described in this chapter. Several potential sediment management strategies for Porto Amboim are proposed and assessed. The second part of this chapter reflects upon the case study results and the applicability of the tool.

Chapter 5: Validation and generic use
This chapter validates the approach and the tool with a second case study on the Tweed River Entrance and expert session to assess the applicability of the decision-making approach.

Chapter 6: Discussion
This chapter covers a discussion on the research limitations and uncertainties.

Chapter 7: Conclusion and recommendation
This chapter concludes the research and give recommendations on further research and advice to Arcadis.

Figure 1.2: Structure of the report

2

Sediment management

A port is an important factor in the water infrastructure since it is the link to overseas transport. A good navigable port is key for efficient port operations. Maintaining the navigability of a port is an essential aspect for efficient port operations, meeting the vessels' demands. Siltation of the channels and basins is the driving process causing the need for sediment management and maintenance dredging in the port. Sediment management needs to be considered during the entire process of the port project. Measures taken in the design phase can have beneficial effects on the required management in the port's operating phase. An accurate sediment management approach is key to optimize the maintenance strategy in a port.

This chapter describes (based on literature research and expert meetings) the sediment dynamics in the port, current ways of sediment management strategies, the potential of sustainable sediment management in the port, and the biggest challenges when finding a sediment management strategy.

2.1. Sediment dynamics in the port

Understanding of the sediment dynamics is important for accurate sediment management. Various hydrodynamic processes drive sediment transport. These processes need to be identified to describe the water exchange and siltation rate in the port. The four main components driving the sediment flows and transport in the port are waves, tide, river flow, and ships.

Sediment can originate from several sources in the system and consist of sand, silt, and mud. The sediment properties play an important role in the siltation processes and the transport patterns of the sediment. These properties need to be considered to find a suitable sediment management strategy.

$$F_s = \alpha * c * \langle Q \rangle \quad \langle Q \rangle = \frac{1}{T}\int_T Q\,dt = \sum \langle Q_i \rangle \tag{2.1}$$

- F_s siltation rate
- α trapping efficiency
- c sediment concentration outside the port
- Q_i exchange rate of water between the port and its environment
  - Q_e exchange of flow by horizontal mixing
  - Q_t exchange of flow by tidal filling
  - Q_d exchange of flow by salinity drive density currents
  - Q_T exchange of flow by warm/cold driven density currents
  - Q_s exchange of flow by sediment-induced density currents

The siltation rate, F_s, in a port basin can be determined with formula 2.1 (lecture notes Sediment Dynamics van Prooijen et al. (2019)). The siltation rate is determined with the basin's trapping efficiency, sediment concentration, and water exchange rate. The water exchange rate (Q) is a combination of different hydrodynamic processes in the port area. A low siltation rate is desired for efficient port operations.

The sediment exchange and siltation rate are mostly driven by water's exchange rate (Q). The water exchange rate is a combination of different hydrodynamic processes as horizontal mixing, tidal filling, and density-driven currents. Decisions made in the first stages of the port design can already influence the exchange rates in the long term. This highlights the importance of a good understanding of the hydrodynamic processes determining the siltation rate and sediment transport patterns (Huguet et al., 2020). The siltation rate can be minimized by reducing α, Q, and/or c. Principles as Keep Sediment Moving, reducing α, and Keep Sediment Out, reducing c, need to be considered to obtain a low siltation rate (Kirby, 2011). Measures considering these principles will be described in the following sections.

2.2. Maintenance dredging techniques

The most used sediment management method in the port is maintenance dredging. Most ports have a contract with a dredging company responsible for the maintenance dredging in the port. Such a contract is based on the required nautical depth in the port, the port operations and vessels entering. The most used dredger for maintenance dredging is the trailing suction hopper dredger (TSHD). As dredging is not the most sustainable operation, interest emerges for more sustainable solutions.

In this section, the most used maintenance dredging techniques are described, additional dredging techniques used for sediment management, and their working principles. Another aspect to consider is the contract form for the dredging operations. The port can have a contract with a dredging company for the maintenance or invest in its own dredging equipment and carry out the maintenance dredging themselves. An optimal combination between the sediment management strategy and the dredging strategy needs to be found for sustainable sediment management in the port.

Trailing suction hopper dredger - TSHD

The TSDH dredges the material from the seabed with a drag head connected to suction pipes alongside the vessel. The dredged material is collected in the vessel's hold and transported to the next disposal location. The TSHD is normally rated according to its maximum hopper capacity, which can currently range from $750m^3$ to more than $45000m^3$ (Laboyrie et al., 2018). The production rate varies between 400 up to $3000m^3/hr$.

To comply with the sustainability requirements in the dredging industry, many improvements and innovations are accomplished in the TSDH design. Examples of the improvements are installing degassing systems, improvements of the overflow with an environmental valve, use of underwater pumps, marine mammal protection, and the transition towards LNG. Other innovations of the previous years are made in more efficient hull design, the economy of scale, more productive hopper loading and unloading system, improved monitoring system, pump efficiency and regulator development, and innovations on the drag head (Arcadis US, 2011). All the innovations are desired to drive the industry towards more sustainable dredging.

Cutter suction dredger - CSD

The CDS is not the most common technique for maintenance dredging but is still suitable for project with hard and thick layers of sediment. The Cutter Suction Dredger (CSD) dislodges material from the seabed and transports it to the vessel with a suction mouth, located in the cutterhead. From the vessel the cut material is transport to the relocation site or into a barge. The CSD is mainly used for capital dredging of hard and thick layers of soil. The CSD has a production rate from 500 up to $3000m^3/hr$.

Backhoe dredger - BHD

Another form of dredger is the backhoe dredger (BHD). The BHD is basically a hydraulic excavator mounted on a pontoon equipped with a spud carriage system. The hydraulic excavator excavates large volumes of material from the seabed and deposits it in a barge. The BHD is mainly used in small projects. The dredge capacity is rated according to the maximum size of the digging bucket, this bucket can range from 1 to $40m^3$, and the excavation depth can vary from 4 to $32meters$ deep (Laboyrie et al., 2018). The production rate of the BHD varies between 100 and $500m^3/hr$ In nearshore projects, it is possible to use a customized elevated excavator (EEX). This EEX is installed in the nearshore zone and can excavate the soil for locations difficult to access by vessel or pontoon. Both dredging methods are pictured in Figure 2.1.

Figure 2.1: Operating BHD and EEX in the nearshore zone (jandenul.com, 2021)

Figure 2.2: Operating WID (damen.com, 2021)

Grab dredger - GD

The grab dredger (GD) consists of a grab and a cable crane mounted on a vessel. The vessel is often equipped with a hold to transport the dredged material. The GD is mostly used in small projects and rated according to its hopper and grab bucket capacity. The dredge's capacity may range from 50 to $2500m^3$, and the grab volume ranges from 0.75 to $200m^3$, although buckets over $20m^3$ are rarely used (Laboyrie et al., 2018), with a production rate between 50 to $500m^3/hr$. The GD is not the most common technique for maintenance dredging but is still suitable for a small and specific project.

Suction dredger - SD

The simplest form of hydraulic dredging is with a suction dredger (SD). The SD is used in areas with relatively loosely packed soil and mostly used for sand-winning purposes. The SD is lowered from a floating platform to its required location, and the dredged material is transport with floating suction pipelines to the disposal location or into a barge. A suction dredge is a suitable option for continuously dredging on one specific location, such as a sediment trap with fluid mud. The SD's pumping capacity ranges widely from 200 to $5,000m^3/hr$ depending upon the size of the SD and the soil characteristics. The suction dredge can be seen as a small dredge suitable for a port authority purchase as its own equipment.

A special method of suction dredging is the submersible dredge pump (SDP). This system consists of a portable dredging head that can be placed on land and in the sea. The SDP can be customized to its application due to the various types of dredging heads (standard suction mouth, plain suction mouth, cutter head, and dustpan head) that can be applied to the system. Therefore is the SDP suitable for small specific projects and difficult to access locations.

Water injection dredger - WID

During water injection dredging (WID), water is injected into the seabed with a fixed array of water jet nozzles. The WID decreases the mud's density and fluidizes the sediment (see Figure 2.2), resulting in a layer of fluid mud near the seabed. This fluid mud layer starts to flow naturally until a new equilibrium is reached. Several ways to interact with this created sediment flow and transport them in beneficial ways out of the port area as described in subsection 2.4.3.

The WID is used in tidal basins to guided fluidized material back into the mainstream, making beneficial use of the ebb currents guiding the sediment away from the basins. The WID is also used to remove sediments from areas difficult to reach by other dredging equipment. The fluidized material can be transported away from these areas into sediment traps or areas where the material can be dredged with other equipment. WIDs are normally rated according to dredging depth or pumping capacity. The dredging depth may range from 5 to $25m$, and the water pumping capacity ranges from 3000 to $12000m^3/hr$ (Laboyrie et al., 2018).

It is important to consider all the possible ways of dredging suitable for sediment management. For sediment management strategy, a combination needs to be found between a sediment management method and maintenance dredging technique.

2.3. Sustainable sediment management

To make sustainable sediment management possible, it is important to acknowledge that sediment from maintenance dredging is an essential component of natural sediment budgets and ecosystems along the coast (Laboyrie et al., 2018). Consideration of accurate sediment management in the port infrastructure is important to optimize the port's interaction with the natural sediment budgets and coastal system. The key principle that should be adopted is; to consider dredged material as a valuable resource used in the natural environment rather than a waste material for disposal (Symonds, 2020). This section describes management approaches to use for sustainable sediment management.

2.3.1. Sediment management hierarchy

Dredged material can be considered as a valuable resource with the zero wast management hierarchy, see Figure 2.3. This approach considers a sustainable way of 'waste' management by minimizing waste and considering waste as a valuable resource. The definition of Zero Waste: "The conservation of all resources using responsible production, consumption, reuse, and recovery of products, packaging, and materials without burning and with no discharges to land, water, or air that threaten the environment or human health. (ZWIA board December 2018, Zero Waste International Alliance (2018))". This is currently the most desired way to consider every form of waste towards sustainable zero waste management.

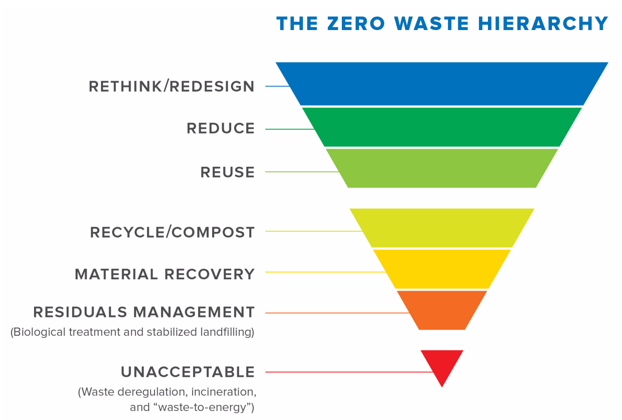


Figure 2.3: The zero waste hierarchy (Zero Waste International Alliance, 2018)

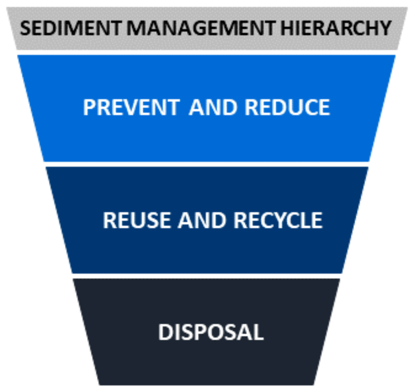


Figure 2.4: Sediment management hierarchy

Based on the zero waste management hierarchy, a sediment management hierarchy (see Figure 2.4) is proposed. This hierarchy aims to adopt dredged material as a valuable resource within the coastal system, using the resource in every step of the approach. This sediment management approach considers three steps.

- **Prevent and Reduce**; the preferred option, considers ways to prevent and reduce siltation in the port, which decrease the need for sediment dredging in the port.
- **Reuse and Recycle**; considers ways to reuse and recycle the dredged material in and around the port, using the material as a resource.
- **Disposal**; the last option considers the possible ways of disposal of dredged material, aiming for the most sustainable solution.

This three-step management approach will be considered in this research for sustainable sediment management in port infrastructure.

2.3.2. Adaptive management

Another interesting management approach for sediment management is adaptive management. This approach is used more and more often in infrastructure and dredging projects. In adaptive management, the management approach is flexible and able to reduce environmental risk through the analysis of monitoring data and to make adaptive decisions. In dredging projects this is, for example, applied through taking decisions to relocate dredging or scale it up or down accordingly as the effects of the dredging activity. Adaptive management is one of the 'key enablers' for sustainable water infrastructure development described by Laboyrie et al. (2018). The enablers contribute to the successful development and implementation and include the most important aspects for sustainable design and management, making them interesting for sustainable sediment management. The 'key enablers' related to design include the need to:

- Aim for 'Added value through multidisciplinary collaboration'
- Achieve 'Stakeholder engagement'
- Align with 'Legislation, regulation and institutional arrangements'
- Assure good 'Contractual arrangements for design and realisation.'

In addition, 'key enablers' that are related to assessment and management include:

- 'Design-related options for environmental gain or mitigation'
- 'Valuation methods for environmental gain'
- 'Key environmental stressors for assessment of the sustainability of a dredging project'
- 'Dealing with uncertainties'
- 'Adaptive management to handle uncertainty within projects'

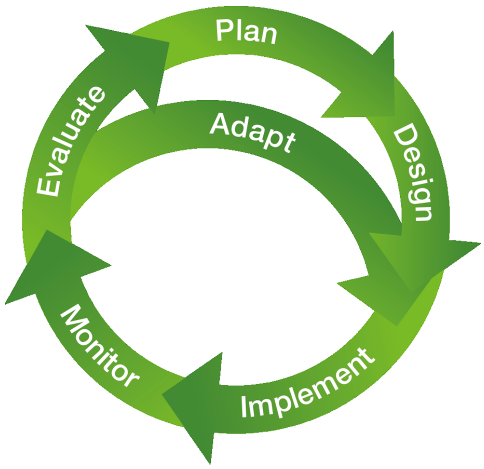


Figure 2.5: The adaptive management steps (van Raalte, 2015)

Applying adaptive management involves: developing a plan that defines the project goals, periodically reviewing progress towards those goals, and, in response to the outcomes of (environmental) monitoring, implementing corrective actions as needed (Laboyrie et al., 2018). This circular management approach (figure 2.5) results in more environmental engagement and adaptive actions to minimize the environmental impact. The steps of adaptive management are listed below and interesting to consider for the sediment management approach.

- *Plan*; defining the desired goals and objectives, evaluating alternative actions and selecting a preferred strategy with recognition of sources of uncertainty.
- *Design*; identifying or designing a flexible management action to address the challenge.
- *Implement*; implementing the selected action according to its design.
- *Monitor*; monitoring the results of outcomes of the management action.
- *Evaluate*; evaluating the system response in relation to specified goals and objectives.
- *Adapt*; adapting (adjusting upward or downward) the action if necessary to achieve the stated goals and objectives.

Dredging for sustainable infrastructure by Laboyrie et al. (2018) also describes a five-step approach that contributes to the development of sustainable infrastructure. This approach for sustainable infrastructure design considers alternative solutions and evaluates the alternatives to find the best fit solution in a sustainable manner. The five-step approach is described below and interesting to consider for sustainable sediment management in the port infrastructure.

Step 1 Understanding the system (including ecosystem services, values and interests).

- The system to be considered depends on the project objectives. The project objectives are influenced by the system (problems, opportunities).
- Information about the system at hand can/should be derived from various sources (e.g. historical, academic, local etc.).
- Look for user functions and ecosystem services beyond those relevant for the primary objective.

Step 2 Identify realistic alternatives that use and/or provide ecosystem services.

- Take an alternative perspective and change more traditional reactive perspectives into proactive ones utilising and/or providing ecosystem services.
- Involve academic experts, field practitioners, community members, business owners, decision-makers and other stakeholders to formulate alternatives.

Step 3 Evaluate the qualities of each alternative and preselect an integral solution.

- More value does not necessarily imply higher construction cost.
- Dare to embrace innovative ideas, test them and show how they work out in practical examples.
- Perform a cost-benefit analysis including valuation of natural benefits.
- Involve stakeholders in the valuation and selection process.

Step 4 Fine-tune the selected solution (practical restrictions the governance context).

- Consider the conditions/restrictions provided by the project (negotiable/non-negotiable).
- Implementation of solutions requires the involvement of a network of actors and stakeholders.

Step 5 Prepare the solution for implementation in the next project phase.

- Make essential elements of the solution explicit to facilitate uptake in the next phase (an appropriate level of detail varies per phase).
- Prepare an appropriate request for proposals, terms of reference or contract (permitting).
- Organise required funding (multi-source).
- Prepare risk analysis and contingency plans.

2.4. Prevent and reduce

There are several methods to prevent and reduce sediment from entering the port and/or reduce the siltation in a port area (Winterwerp (2005), Kirby (2011), van Rijn (2016)). It is important to identify all the different options and find the most suitable method and strategy for each port. Complete prevention of sedimentation is ideal but very difficult to achieve. However, several measures are capable of reducing the sedimentation rate of sand and silt significantly. The methods described in this section will be addressed and compared when optimizing the sediment management strategy for a port.

The prevention measures described in this section are divided into *sediment control*, *reducing structures*, and *sediment resuspension* (see Figure 2.6). Sediment control discusses the sediment managing options controlling the location and accumulation process of the sediment. Reducing structures are structures blocking or redirecting sediment, reducing the inflow of sediment in the port. The last method describes prevention measures resuspending the sediment to decrease the sedimentation rates and creating fluid mud, mostly applicable for silt. A short description about the working principle of the prevention measure is given, followed by the potential for sustainable sediment management. A more detailed description of each method with examples of applications and projects can be found in appendix A.

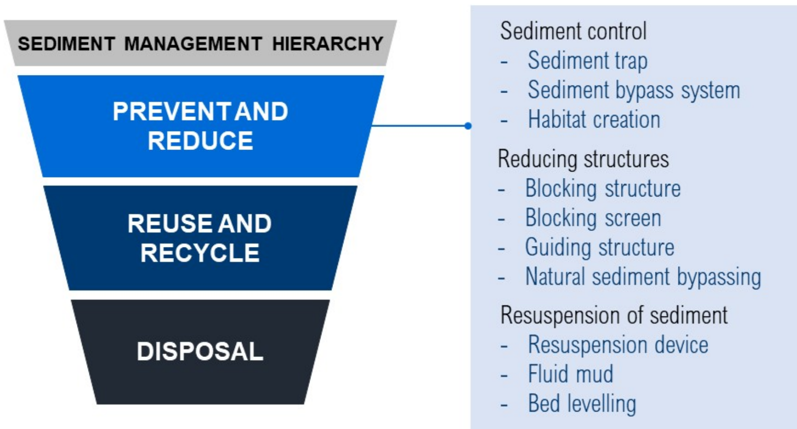


Figure 2.6: Sediment management hierarchy: prevent and reduce

The prevention measures described in this section address three principles (Kirby, 2011). These principles aim for sustainable sediment management and minimization of port siltation. The principles aim to reduce α, KSM, and reduce c, KSO, resulting in a lower siltation rate (see 2.1). The three principles are explained below.

- **Keep sediment out (KSO)** keeping sediment out of the area of interest that might otherwise enter and accumulate.
- **Keep sediment moving (KSM)** raising flow velocities in the port area to prevent sediment from settling as it is transported through and out of the area of interest.
- **Keep sediment navigable (KSN)** keeping the sediment navigable in the area of interest, applicable to sites characterized by high turbidity near-bottom sediment regimes and muddy beds.

2.4.1. Sediment control

This section describes methods to control sediment and stabilize the sediment source in the area of interest. An area is created, or a measure is taken to control the accumulation location or natural sediment flow. In the proposed methods, the principles *keep sediment out* and *keep sediment moving* are both applied. The prevention measures aim to extend the period between two dredging campaigns. This is achieved by decreasing the need for dredging and can reduce the environmental impact, the cost, and the emission of the sediment management strategy. This is achieved by controlling the settlement's location and/or moving the sediment, resulting in efficient sediment management. The following three prevention measures have the potential to control the sediment in the port infrastructure and are researched in this thesis.

Sediment trap
A sediment trap is a storage location for sediment to accumulate before dredging. Sediment traps can be located inside the port basins or outside the port. Locating a sediment trap outside the port creates the possibility to store the material outside the zone of navigation between two dredging campaigns. A dredged trench, the trap, reduces flow velocities in the above water column and decreases the capacity to transport sediment. This reduction results in sediment settlement. The sediment is stored in the trap at a specific location, sediment control. This method does not generally decrease the volume of dredged material required. Still, it can reduce the unit cost of dredging by avoiding interference with navigation during dredging operations, shortening the distance to the disposal area, or reduce the need for dredging in difficult to reach areas. The main working principles of the sediment trap are:

- Decreasing the sediment transport capacity.
- Trapping sediment in a preset location with created additional depth.
- Creating an attractive environment for accumulation.

Potential for sustainable sediment management
The high trapping efficiency and controlled area of accumulation of this method make it an interesting method for efficient sediment management. The method can be applied to *keep sediment out* or reduce the time between two dredging campaigns. It is important to identify the sediment trap's capacity and make an assumption about the trapping efficiency.

- Challenges
  – Not reducing the total volume that needs to be dredged.
  – Difficult to predict its efficiency of the sediment trap.
  – An optimal trapping location and configuration of the trap need to be determined.
- Potential
  – Traps the sediment before entering or in the port.
  – Keeps sediment out in a trap outside the port.
  – Sediment settles on a controlled location.
  – Extends the period between to dredging campaigns.

Sediment bypass system
The sediment bypassing system's general concept is passing the sediment by a port entrance or river mouth with an installed jet, suction and pump system. The sediment bypass system contributes to the natural littoral drift. The sediment is caught at the upstream side and deposit at the downstream side of the bypassed area, where it can continue in its natural littoral drift direction. A bypass is generally constructed to overcome the littoral drift's interruption by a river or port entrance, an example of a system is given in Figure 2.7. Sediment bypass projects generally have two main principles:

- Maintaining the bypassed area's navigability prevents sediment from accumulated and moved in the channel or port.
- Nourishing the adjacent coastline at the downstream side of the bypassed area.

Potential for sustainable sediment management
A well-designed sediment bypass system fit to the port's characteristics can optimize the sediment management in the port.

- Challenges
  – High investment cost.
  – Frequent maintenance and monitoring of the system needed during operation.
- Potential
  – Keeps sediment out and bypasses it around the port.
  – Manages the longshore sediment transport.
  – Maintains the sediment balance in the downstream area of the port.

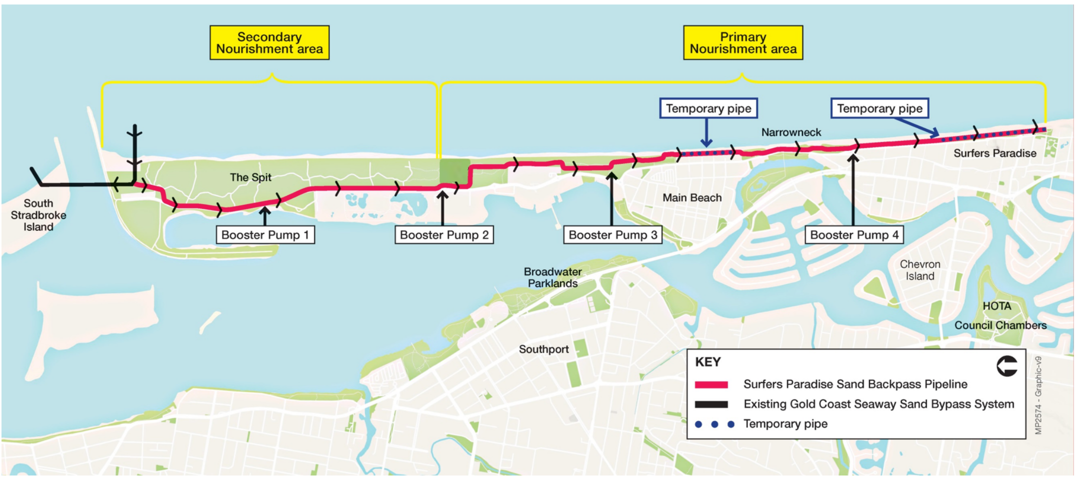


Figure 2.7: Sediment bypass system: Gold Coast Seaway Sand Bypass System and the Surfers Paradise Backpass Pipeline used for sediment management along the Gold Coast beaches and the Gold Coast Seaway. (City of Gold Coast, 2020)

Habitat creation

Habitat in the surrounding areas of the port promotes both the accretion of sediment and improvement of the ecosystem. Mangroves, salt marsh, and seagrass are suitable plants to place in such habitats; they lower the hydrodynamic load and stimulate sediment accumulation. Creating or restoring habitat in the port area can reduce the amount of sediment entering the port, as these habitats attract sediment to settle and stabilize the sediment balance. This method is based on the working principles:

- Creating an attractive area for sediment to settle outside the port.
- Adding new habitat to the port environment.

Potential for sustainable sediment management

The stabilization of sediment and the positive impact on the environment make this measure interesting for sustainable sediment management.

- Challenges
  – Difficult to predict the method's efficiency.
  – A large area of vegetation is needed to be efficient.
- Potential
  – Gives an additional ecological value to the port surroundings.
  – Keeps sediment out by trapping it in the vegetation.
  – This is a nature-based solution.

2.4.2. Reducing structures

This section describes methods to reduce siltation in the port area by *keeping sediment out* and *keep sediment moving*. To obtain this, a structure needs to be placed in the port area, an invasive mitigation measure with beneficial effects in the long term. Different possibilities and methods are described in this section. A short explanation of prevention measures gives insight into the characteristics and potential of the method for sediment management.

Blocking structure

A blocking structure blocks the sediment flow into the port. The principle considers in this method is *to keep sediment out*. This blocking is possible with a structure blocking the sediment transport before entering the port or at the port entrance. Structures, for example, groynes, are often used to block sediment transport along the coast to maintain the beaches and avoid erosion. Constructing groynes along the coast in the port area can create the same effect. Sediment is trapped and blocked before entering the port and managed from this location, reducing the sediment flow into the port. It is also possible to construct a bigger blocking structure like a sluice at the port entrance. The main working principle of this method is:

- Blocking the sediment flow before it can enter the port.

Potential for sustainable sediment management
As the blocking structure reduces the sediment flows into the port and traps or blocks the sediment before the port, it is a method that can be used in a sediment management strategy. It is a measure interesting to consider if there is one sediment transport direction dominating the port area.

- Challenges
  - Method can cause hinder for navigation.
  - A relatively large structure need to construct.
  - Monitoring is required to see the efficiency of the method.
  - Difficult to dredge buffer near the groyne on the beach, high cost.
  - Another measure needs to be used to restore the sediment balance downstream of the port.
- Potential
  - Keeps sediment out of the port.
  - Control of sediment in a specific location outside the port.
  - Blocks sediment flow into the port.

Blocking screen
A blocking screen acts as a physical barrier between the port or basin entrance and the surrounding area. The barrier functions as it blocks the sediment from entering the port while still allowing vessels to pass, *keeping sediment out*. The blocked sediment is stimulated to *keep moving* and guided away from the port or basin, see Figure 2.8. Examples of such barriers are silt screens, bubble screens, or even a gel screen has the potential to block sediment from entering and still allow vessels to pass. The principles of this prevention method are:

- Preventing sediment from entering a certain area by blockage with a physical barrier.
- Keep sediment moving outside the port.

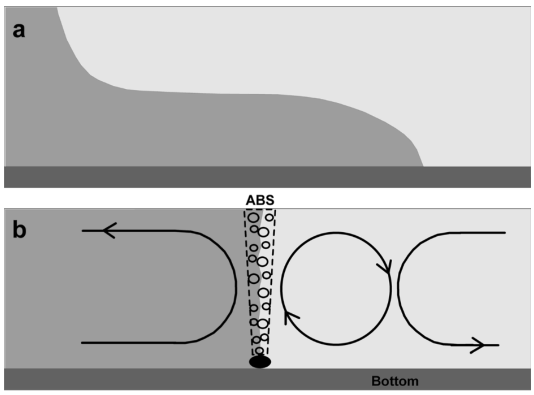


Figure 2.8: Circular vertical flow generated by an air-bubble screen (ABS) in case of a density flow (a). The ABS in the water column is indicated with a dotted area of bubbles. (Cutroneo et al., 2014)

Potential for sustainable sediment management
As a blocking screen can function as a physical barrier for sediment, it has the potential to be used in sediment management strategies.

- Challenges
  - An expansive structure to construct and maintain.
  - Needs to be in operation continuously.
  - High energy demands and emissions levels.
  - No information about the gel screen and proof of concept yet.
  - Sensible for environmental variability and extreme events in the area.
- Potential
  - Blocks the sediment from entering the port with a physical barrier.
  - Vessels are able to pass the barrier.
  - Keeps the sediment moving and out due to the vertical circulation.

Guiding structure
Keep sediment moving and *keep sediment out* is the principle behind this method. Training walls, sills, and other diverting structures like a current deflecting wall (CDW) are placed to guide currents and increase circulation in the port (see Figure 2.9). The structures prevent the sediment from settling or redirected the flow away from the port. This method is often used in rivers and at a river mouth but also suitable for port and basin entrance channels where high flow velocities occur. This method is interesting for ports where high tidal or river velocities are present. The working principle of a guiding structure is:

- Guiding the sediment flow in the area away from the port basin and to keep it moving.

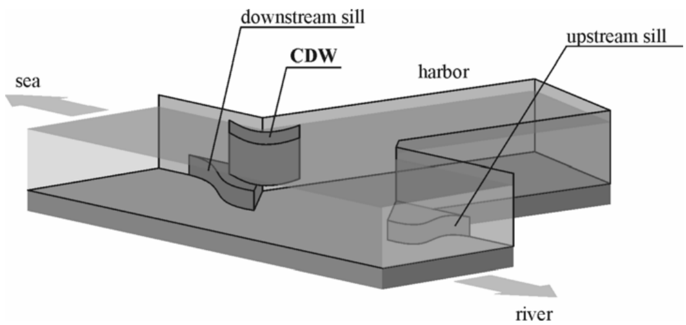


Figure 2.9: Current deflecting wall at a port basin entrance (Stoschek et al., 2003)

Potential for sustainable sediment management
A well-designed guiding structure can stimulate the flow and sediment patterns in the port area. This enhances the sediment transport rate and decreases sediment accumulation. This working principle makes this method interesting for sediment management in a port environment where high flow velocities occur.

- Challenges
  - Needs an optimized design for the specific location.
  - The structure can cause hinder to navigation.
  - Maintenance of the structure is needed.
  - Relatively large structure.
- Potential
  - This method keeps sediment out of the port area.
  - Keeps sediment moving in the port's basins and channels.
  - Interacts with the natural flows and tidal currents to enhance the sediment flow.
  - Deflects the sediment from entering the port's basins and channels.

Natural sediment bypassing
Natural sediment bypassing can be increased in ports due to the construction of well-designed breakwaters. Two streamlined breakwaters located at the port head increase the bypass of sediment past the harbour head by increasing the flow velocity due to contraction around the head, an example is given in Figure 2.10. The increased flow bypasses the sediment around the harbour head, decreasing the sediment amount flowing into the port. The main working principle of this method is:

- Enhance natural sediment bypassing around the channel entrance and keep the sediment moving.

Potential for sustainable sediment management
This method is interesting for sustainable sediment management if the right balance is found between the maintenance dredging, natural depth, navigation depth, and littoral transport. Stimulating sediment's natural bypassing can play an important role in maintaining the sediment balance in the port area. It can decrease the need for regular maintenance dredging, making it interesting to consider.

Figure 2.10: Proposed layout of Hvide Sande harbour breakwaters (curved yellow lines) and coastline location obtained with a capital dredge to enhance natural bypass of sediment. (Hillen et al., 2009)

- Challenges
  - Requires optimal and intensive design to optimize the natural bypassing.
  - Large structure needs to be constructed.
  - Monitoring required to indicated when bypassing rate reduces and dredging is needed.
  - Not efficient if large nautical depths are required in relation to the natural depth in the area.
- Potential
  - Bypasses the sediment around the port entrance.
  - Keep sediment out and moving.
  - Makes beneficial use of the natural littoral drift and improves the sediment balance.

2.4.3. Resuspension of sediment

In this section, methods are discussed to keep sediment in suspension and resuspend the sediment. The different methods aim to *keep the sediment moving* (KSM) and *keep sediment navigable* (KSN) to reduce the need for maintenance dredging. For these methods, mechanical devices are still needed, but they can operate more efficiently and with fewer emissions than maintenance dredging. The methods aim to replicate the regular natural resuspension of recently deposited bed sediment to prevent ongoing siltation. A short description of the method gives insight into the working principles and the potential for sustainable sediment management.

Resuspension device

An increased bed shear stress keeps sediment moving and in suspension. Devices used to adopt this approach are hydraulic jets, propellers, vortex foil arrays, ejectors, and mechanical agitators. Attaching the devices to quay walls or placing them on the seabed of an entrance channel generates currents resuspending the sediment, keep the sediment moving, and remove the sedimentation. The resuspended sediment flow can be transported out and away from the port with the tidal and gradient currents, making it an interesting sediment management method. The working principles of the resuspension devices are:

- Bring sediment in suspension again, allowing it to move away from the port entrance or basin.
- Make the resuspended sediment navigable.
- Or remove the settling sediment.

Potential for sustainable sediment management

Stimulating the sediment flow and creating a navigable fluid mud layer make this prevention measure interesting for sediment management. Especially for ports where high concentrations of fine sediment occur, is this an interesting method, decreasing the need for regular maintenance dredging.

- Challenges
  - Needs to be in operation continuously to avoid sediment accumulation.
  - The system or devices have high energy consumption.
  - Could influence the navigation safety in the port near the installation.

  - Possible hinder or interaction with the port operations.
- Potential
  - Keeps the sediment moving in the port.
  - Decrease the amount of needed maintenance dredging.
  - Keeps the sediment navigable and increases the nautical depth.
  - Removes the sediment from the channel.

Fluid mud
Another principle with potential is navigating through fluid mud. This method creates a fluid mud layer through which vessels can sail, *keep sediment navigable*. Water injection dredging (WID) is used in ports to resuspended sediment, stimulating sediment flow out of the port and creating fluid mud layers. The density properties of fluid mud allow vessels to sail through the mud enlarging the nautical depth of the port's channels and basins. The main principle of this method is:

- Create a fluid mud layer with a resuspension device or dredge.
- Increase the nautical depth with a fluid mud layer through which vessels can sail.

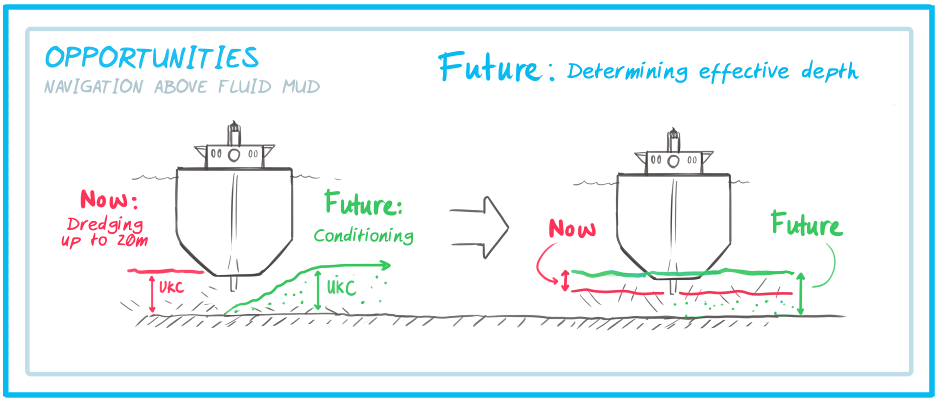


Figure 2.11: The opportunities of sailing through fluid mud, increasing the nautical depth (smartport.nl ,2021)

Potential for sustainable sediment management
Fluid mud is interesting for sustainable sediment management in large ports with fine sand and silt (see Figure 2.11. The increased nautical depth obtained with WID decreases the need for maintenance dredging. A balance between the dredging methods and the interaction with the vessels need to be found to obtain a good sediment management strategy with fluid mud.

- Challenges
  - Difficult to predict the exact nautical depth in the fluid mud.
  - Trust in fluid mud of the sailors needed.
  - Monitoring of the fluid mud layer needed to ensure the required depth.
- Potential
  - Keeps the sediment moving.
  - Decrease the amount of needed maintenance dredging.
  - Keeps the sediment navigable.
  - Reduce the total CO_2 impact, as WID is more CO_2 efficient.
  - Beneficially uses the properties and potential of fluid mud.

Bed leveling
Bed levelling is used to reduce the need for maintenance dredging by redistribution of sediment. During bed levelling or drag barring, a heavy metal bar is lowered to a certain depth and dragged across the seabed. This method keeps the bed equally levelled and smooth. Drag barring is also used to redistribute the accumulated sediment across the bed. Unevenness in the bed increases accumulation rates and causes siltation. The smooth bed *keeps the sediment moving* and stimulates flows through the port basin. The process can also result in some fine-grained sediment resuspension, which, if the

currents are strong enough, will be transported away from the port area. The working principles of this method are:

- Levelling the bed to decrease accumulation rates.
- Redistribute sediment across the bed to avoid large accumulations and pits in certain areas.

Potential for sustainable sediment management
This method aims to reduce the accumulation rates by *keeping the sediment moving* and redistributing the sediment. The method has the potential to be used in a sediment management strategy.

- Challenges
  – Needs to be carried out quite often to be efficient.
  – Hinders the normal port operations.
  – Limiting to be efficient over certain depths.
- Potential
  – Keep sediment moving.
  – Decrease the amount of needed maintenance dredging.
  – Can be carried out by the port itself for local maintenance in specific areas of the port.
  – Can be used in berth areas difficult to assess.

These are the ten prevention measures with the potential for sustainable sediment management in the port infrastructure. These measures will be used further in the research of the thesis. Not all measures are suitable for every port; the best fit prevention measure needs to found for each port. The next chapter, decision-making approach, will describe how to find the best sediment management method and strategy for each port.

2.5. Reuse and recycle

Considering dredged material as a valuable resource rather than a waste makes it interesting for reuse and recycling. Various beneficial reuse and recycle options have the potential for dredged sediment and described in this section. The reuse and recycle methods are divided into three categories *engineering use*, *environmental enhancements*, and *product use*, see Figure 2.12. Further descriptions of the methods and examples of successful projects explaining the reuse and recycling techniques' potential can be found in appendix B.

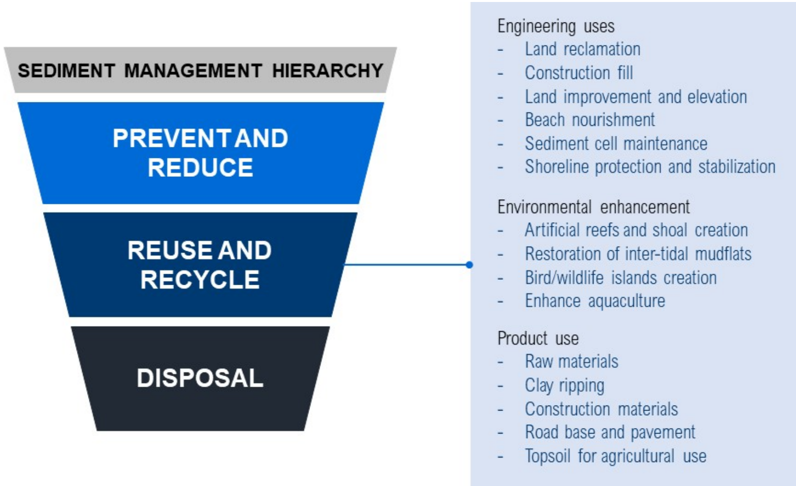


Figure 2.12: Sediment management approach: reuse and recycle

2.5.1. Engineering uses

Dredged material is reused in engineering projects onshore and offshore. Several examples of engineering use are listed below. First, onshore recycle options are given, followed by offshore reuse. In the onshore projects, the dredged material is mixed or treated before usage. After the treatment, the material is suitable to use in engineering projects, meeting the technical requirements. Offshore sediment is often used to support and interact with the natural system. In offshore engineering projects, untreated dredged material can be used. Several examples of engineering projects reusing dredged material are:

- Land reclamation
- Construction fill
- Land improvement and elevation
- Beach nourishment
- Sediment cell maintenance and berms
- Shoreline protection and stabilization

2.5.2. Environmental enhancement

There are various options to reuse dredged material to create and restore habitat and to enhance the port surroundings' environment. The dredged material can be used beneficially in several projects onshore, nearshore, and offshore, for example:

- Artificial reefs and shoals restoration and creation
- Restoration of inter-tidal marshes and mudflats
- Bird/wildlife islands creation
- Enhance aquaculture

2.5.3. Product use

Sediment is a valuable resource, and it can be reused and recycled as a product. Different options are possible because of the varying properties of the sediment and dredged material. Some of the options for product use are:

- Raw materials

- Clay ripening (see Figure 2.13)
- Construction materials
- Road base and pavements
- Topsoil for agricultural use

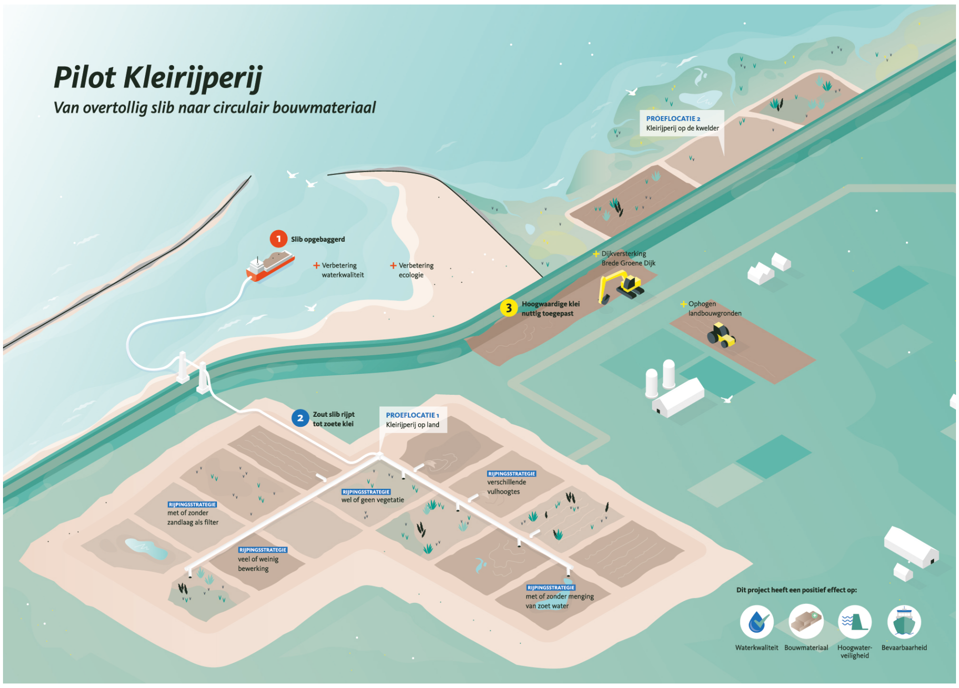


Figure 2.13: Kleirijperij pilot project identifying various ways to reuse silt from the Eems-Dollard region (Ecoshape - NL, 2020)

There are various possible reuse and recycle options to use the dredged material. Considering the material as a valuable resource has good potential for sustainable sediment management in the port infrastructure. It is time to look at the complete cycle and not just focus on removing the sediment. These possibilities will be considered further in the research. Not all measures are suitable for every port; the best fit needs to found for each port. The next chapter, decision-making approach, will describe how to find the best strategy for each port.

2.6. Disposal

Sometimes there is no option to reuse the dredged material, resulting in the last option, sediment disposal. This is only an option when: the material cannot be reused or the material cannot be treated to a complying level of reuse. There are still three different disposal options suitable for material disposal. The first option is disposal in areas with lost purpose. The second option is disposal at an offshore disposal site. The last option is onshore disposal at a sediment depot. The best options depend on the options available and the level of contamination. Countries have quite often signed an international environmental seawater protection agreement, but the local legislation still needs to be assessed for every individual port project to consider the available options.

Areas with lost purpose

Areas with lost purpose are, for example, borrowed pits and dead-end channels. Depositing dredged material in these areas can even have beneficial effects on the surrounding environment. Borrowed pits are deep former sand pits created during land reclamation, often are these pits located in the port area. Disposing material in these pits is beneficial because it can improve the hydrodynamics and water quality in the area. Another advantage is that these pits are located close to the dredged area, decreasing the transport distance. Dead-end channels occur in low dynamic parts of the port area and are characterized by low water quality. Filling these dead-ends is beneficial for the water quality and the hydrodynamics in these channels (Yozzo et al., 2004).

Offshore disposal site
Offshore disposal is still the most common option used in maintenance dredging strategies, with the primary goal of reallocating the system's material. Offshore disposal areas are indicated by the local government, often according to an international environmental seawater protection agreement such as the London convention of 1972 or the London protocol of 1996 (Arcadis Nederland BV and JESyCA S.A.S., 2017). The site is located not too far from the port to minimize the transport cost.

Onshore disposal site
In some cases, it is not possible to deposit the material at one of the above sites. The reason for this is quite often the level of contamination in the dredged material. In some ports, onshore disposal sites are created to store this contaminated sludge. An example of such a disposal site in the Port of Rotterdam is the Slufter located in the southwestern part of the Maasvlakte. A landfill is the last option to consider if disposal in the port area is not an option. This option is the least desired but still a way to managed highly contaminated dredged material.

2.7. Challenges

According to the literature research on several case studies and several expert meetings, the biggest challenges of sediment management strategies are:

- Cost and benefits
- Environmental factors
- Uncertainty in design and system response
- Varying stakeholder interests
- Maintenance techniques
- Long term benefits
- Extreme events

These challenges indicate the important aspects of sediment management and the uncertainties to overcome. It is important to consider these challenges in the approach towards a sustainable sediment management strategy.

The following chapter describes the approach to optimize the management strategy and find the most suitable prevention measures for the port. To obtain this approach towards a sustainable sediment management strategy, the management approaches from this chapter are used together with the described the prevention, reuse, and recycle measures. This chapter can be considered as the foundation of the further research.

3

Decision-making approach

Various aspects make it challenging to find the optimal sediment management strategy for a port. A structured decision-making approach supports the process towards a good and sustainable strategy for a port. This approach focuses on the optimization of the sediment management strategy of an existing port. This chapter describes the decision-making approach based on the sustainable sediment management hierarchy, examples of sediment management methods, interviews, sediment management challenges, and port case studies.

3.1. Approach

Finding the right sediment management strategy and prevention method for a port is a challenging process. Port specific characteristics and stakeholder interests influence the results and decision-making process. To obtain the most suitable sediment management strategy and support the decision-making process, a four-step decision-making approach (see Figure 3.1) is proposed. This approach is based on the management approaches described in the previous chapter. The four-step decision-making approach is given below:

1. Analysis of the current state of the system, maintenance, and sediment management - *Sediment management objectives*
2. Pre-assessment of possible prevention methods for the sediment management strategy - *Fit to case*
3. Assessment of the potential sediment management strategies for the port with the decision-making tool - *Assessment of potential strategies*
4. Meeting the objectives with a long-term sediment management and maintenance strategy for the port - *Application of the strategy*

Figure 3.1: Decision-making approach towards a sustainable sediment strategy for a port

In *Dredging for sustainable infrastructure* by Laboyrie et al. (2018) a five-step approach for the design of sustainable infrastructure is defined. This approach contributes to the development of sustainable infrastructure and alternative solutions will be created and evaluated by this approach to find the best fit solution in a sustainable manner. As sediment management is part of the port's infrastructure and a more sustainable management strategy is required, this approach is used to develop the decision-making approach. The Table 3.1 below summarizes the steps of both approaches and describes the implementation of the *design of sustainable infrastructure* approach in the *decision-making approach*.

	Design of sustainable infrastructure	Developed decision-making approach
1	Understanding the system	Sediment management objectives
	Consider the project objectives, gather information from various sources, and look for user functions and ecosystem services beyond those primarily relevant	In this step of the approach the sediment management objectives follow from an analysis of the current state of the system.
2	Identify realistic alternatives that use and/or provide ecosystem services	Fit to case
	Take an alternative perspective providing ecosystem services, and involve various stakeholders to formulate alternatives.	The sediment management hierarchy is considered to find potential prevention, reduce, reuse, and recycle methods for the sediment management strategy. This hierarchy stimulates to find alternative solutions for the case.
3	Evaluate the qualities of each alternative and preselect an integral solution.	Assessment of potential strategies
	More value versus cost, embrace innovative ideas, perform a cost-benefit analysis, and involve stakeholders	The potential strategies, alternatives, are assessed within various categories using performance indicators.
4	Fine-tune the selected solution.	Application of the strategy
	Consider the conditions and restrictions, and get the required involvement for the implementation of the solutions	Following from the assessment a long term sediment management strategy of the port will be proposed. The proposed strategy should meet the objectives. Further steps of implementation are not considered in this research.
5	Prepare the solution for implementation in the next project phase	*next project phase not considered in this research*

Table 3.1: A summary of the decision-making approach for sustainable sediment management in and the design of sustainable infrastructure approach (Laboyrie et al., 2018).

The decision-making approach considers most of the aspects from the literature approach, Table 3.1. It considers a more detailed approach focusing specifically on sediment management in a port and leaves the implementation phases out. In the following section the steps of the decision-making approach are further described.

3.2. Sediment management objectives

In the first step, the sediment management objectives are defined based on an analysis of the system's current state. The analysis of the current state of the coastal system, the applied maintenance strategies, and a stakeholder analysis provides information about the port. A good understanding of the current state of the system and the developments over the years since the construction of the port is important to find the best fit sediment management strategy. Events from the past can provide information about the system's behaviour and help find an improved strategy. Information on the following aspects is required to understand the current system and find the objectives of the sediment management strategy for the port. The required information is described below:

- *Coastal morphology*: gives information about the hydrodynamics in the port and the coastal morphology in the area around the port.

- *Sediment balance*: gives information about the sediment source, transport rates, and sediment transport patterns in the port area.
- *Port operations*: gives insight into the port operations, growth and required water infrastructure of the port.
- *Stakeholders*: a stakeholder analysis provides insight into the stakeholder interests, needed requirements and importance of certain indicators.
- *Environment*: gives insight into the local ecosystem and environmental impact of the port.
- *Sediment management strategy*: explains the current strategy to ensure a good navigable port.

The analysis of the current state of the system is the basis to formulate the objectives for the strategy. With this analysis, specific objectives for the sediment management strategy can be defined. These objectives determine the goals of the sediment management strategy for the port in consideration, based on the stakeholders' interests and desired future state of the system. The general strategic objective for sustainable sediment management is:

> *Strategic objective*: Improve the sediment management strategy in the port in a sustainable way and obtain a long-term solution.

This objective is the starting point of the process towards an optimal sediment management strategy for a port and supported by the port-specific sediment management objectives. The following sections describe the further steps of the decision-making approach and decision support tool to meet the objectives and find the best fit sediment management strategy.

3.3. Fit to case

As every port is different and has different objectives for its sediment management strategy, a *fit to case* strategy needs to be found. To find a strategy the sediment management hierarchy is considered; Prevent and Reduce, Reuse and Recycle, followed by Disposal. In Section 2.4, several prevention methods to manage sediment in the port are described. This step, *fit to case*, selects the potential prevention methods for the port to include in the strategy. With the system analysis and the objectives, the prevention methods with the most potential can be selected. The ten different prevention methods are:

Sediment control
- Sediment trap
- Sediment bypass system
- Habitat creation

Reducing structures
- Blocking structure
- Blocking screen
- Guiding structure
- Natural sediment bypassing

Resuspension of sediment
- Resuspension device
- Fluid mud
- Bed levelling

Not all the prevention methods are suitable for each port and its specific characteristics. First, the most suitable prevention method need to be chosen to continue with the assessment. A combination of two methods can also be the most suitable solution for sediment management in the port. The selection of the most suitable prevention methods is based on the port's characteristics and the sediment management strategy's objectives obtained in *step 1*.

The port characteristics determining the most suitable prevention methods are defined by the coastal morphology, the sediment's source, and the sediment properties. The prevention measures' efficiency varies depending on the influences of a river, tidal currents or wave currents. The dominating hydrodynamic process determines the most suitable solutions. The sediment properties also influence the most suitable prevention measures and vary from coarse sand to fine silt.

	Sediment trap	Bypass system	Habitat creation	Blocking structure	Blocking screen	Guiding structure	Natural bypassing	Resuspension device	Fluid mud	Bed levelling
Sedimet management	Traps and stores sediment in a specific area, the sediment trap.	The bypass system pumps the sediment around the port	The vegetation in the habitat enhance the trapping efficiency outside the port	The blocking structure blocks sediment transport and flow outside the port	The blocking screen blocks sediment entering while allowing vessels to pass	Guiding structures prevent sediment from settleing and reflect the flow away from the port	A structure enhances the sediment transport rate stimulating natural bypassing	Devices prevent sediment from settling resuspened sediment enhancing the flow	Devices resuspend sediment creating fluid mud making sediment navigable	A leveled bed decreases the sedimentation rate
Principle	KSO	KSO	KSO	KSO	KSO & KSM	KSO & KSM	KSO & KSM	KSM & KSN	KSM & KSN	KSM
Sediment	Sand - silt	Sand	Sand - silt	Sand - silt	Sand - silt	Sand - silt	Sand - silt	Silt	Silt	Sand - silt
Working principles	Decrease transport capacity by creating an attractive settling area Trapping of sediment in specific location	bypassing of sediment nourishing the downstream area	Creating an attractive sedimentation environment Adding new habitat to the port environment	Block the sediment before entering the port	Preventing sediment form entering with a physical barrier Stimulate flow circulation	Guiding the sediment flow to keep it moving Deflecting the sediment flow away from the port	Enhance natural sediment bypassing Deflecting the sediment flow away from the port	Bring the sediment in suspension again Create navigable sediment	Create a navigable fluid mud layer Increase the navigable depth	Levelling the bed to decrease accumulation rates Redistribution of sediment across the bed
										
REDUCE										
Reduction of port siltation [%] after the measure	10-50%	up to 90%	dificult to predict	40-80%	up to 90%	40-50%	40-50%	difficult to predict	30-60%	difficult to predict
FINANCIAL										
Cost indication [$]		> $7.000.000						> $2.500.000		
The cost of **the investment** compaired	Dredging cost trap	System cost	Cost habitat creation	Cost of the structure	Cost of the system	Cost of the structure	Cost of the structure	Cost of the system		Cost of the system
The **operational cost** compaired to the initial operational cost	Cost for maintenance dredging	Operational cost	Cost for maintenance dredging	Cost for maintenance dredging	Operational cost and cost for maintenance dredging	Cost for maintenance dredging	Cost for maintenance dredging	Operational cost and cost for maintenance dredging	Cost WID and cost for maintenance dredging	Operational cost and cost for maintenance dredging
OPERATIONAL										
The need for **maintenance** and **operational work** of the measure		System operations and maintenance			System operations and maintenance			System operations and maintenance	Operations of fluid mud with WID	Operational, bed levelling
The need for **maintenance dredging** in combination with this	Maintenace dredging to empty the trap and the siltation in the port	Some maintenace dredging if not all the sediment is bypassed	Maintenace dredging of the remaining port siltation	Maintenance dredging near blocking structure and in the port	Some maintenance dreding if not all the sediment is blocked	Maintenance dredging of the remaining port siltation	Maintenance dredging of the remaining port siltation	Some maintenance dredging if not all the sediment is resuspended	Maintenance dredging of the remaining port siltation	Maintenance dredging of the remaining port siltation
RESOURCES										
The emitted **CO_2 and NO_x** during the operations	Emission during dredging	System emissions	Emission during dredging	Emission during dredging and construction	System emissions and during dredging	Emission during dredging and construction	Emission during dredging and construction	System emissions and during dredging and construction	Emissions during dredging	Emissions during operation and dredging
ENVIRONMENTAL										
The impact on the **biodiveristy** due to the measure		Stimulates natural littoral drift	An addition to the environment and ecosystem			Stimulates natural flow	Stimulates natural littoral drift		Uses the benefits of fluid mud	
COMMUNITY										
New **jobs** for the local community		New jobs in operations			New jobs in operations			New jobs in operations	New jobs in operations	New jobs in operations
Positive **impact** on the local community		Innovative system and jobs and responsibility	Enhancing of the environment					Innovative system and jobs and responsibility		

Figure 3.2: Overview of characteristics of the prevention methods (screen snip from decision-making tool)

Some of the prevention measures are not efficient in a silt dominated area and more workable when only sand occurs in the area. The coastal morphology and the sediment properties are important aspects to consider when selecting the most suitable solutions. Figure 3.2 gives an overview of the prevention measures, the characteristics of the methods, and the suitability in certain environments. The table can be used to define the potential strategies for the port.

The selected potential strategies will be assessed in the next step, *Assessment of potential strategies*, to find the most suitable strategy for the port. The following section describes the assessment process with the supporting *Microsoft Excel*-tool.

3.4. Assessment of potential strategies

When suitable prevention methods are found, the potential sediment management strategies can be formulated. The potential strategies are worked out in more detail specific for the port. In this preliminary design, a more detailed strategy is described considering sediment management requirements, the prevention method, required additional maintenance dredging and the reuse and recycle options. All available information about a case study is used to define this preliminary design. The best fit for the port is assessed with the potential strategies. To perform the assessment, a decision support tool is developed supporting the process towards the best sediment management strategy for the port.

The potential strategies will be assessed on seven categories. The categories are based on port case studies, the characteristics of the sediment management methods, and IFC's Environmental and Social performance standards (World Bank Group (2017), International Finance Corporation (2012)). The seven categories contribute to the overall objective: *Improve the sediment management strategy in the port in a sustainable way and obtain a long-term solution* and consider all the important aspects of a sediment management strategy. The seven categories are listed below:

- **Reduce** this category describes the reduction of sedimentation in the port.
- **Financial** this category gives information about the financial performance of the strategy, which makes it possible to compare the investment and operational cost.
- **Operational** this category indicates the operational needs and performance of sediment management strategy.
- **Resources** this category indicates the resources management.
- **Environmental** this category indicates the performance of several environmental aspects, which are important for the coastal system and the port.
- **Community** this theme gives information about the impact on the community when applying the sediment management strategy.
- **Durability** this category indicates the lifetime of the strategy and the long term performance.

Figure 3.3: seven categories - performance indicators

The developed tool consists of four components supporting the decision-making approach and considering the categories. The components are used to assess the potential strategies and compare them on several aspects and the categories. The four components of the tool are listed below:

1. *Performance indicators* - Assessment of potential sediment management strategy per category with the performance indicators

2. *Effectiveness* - Assessment of the effectiveness of the working principles of the strategy
3. *Quantification* - Detailed description of certain performance indicators of the strategy
4. *Sensitivity analysis* - Analysis of the sensitivity and stability of the results of the assessment

3.4.1. Performance indicators

The potential alternative strategies and the initial strategy are assessed with performance indicators subdivided into seven categories in the decision support tool. The first step is to select the performance indicators for the assessment of the potential strategies for the case. These indicators assess the challenges of sediment management and the objectives from *step 1 - Sediment management objectives*. Below various important performance indicators are described subdivided into the categories. For a complete assessment it is required to choose at least one performance indicator in each category.

Reduce

- *Reduction*: indicates the amount of reduction of sedimentation obtained by the strategy.

Financial

- *Investment cost*: indicates the investment cost.
- *Operational cost*: indicates the operational cost of the strategy.

Operational

- *Maintain accessibility*: indicates the ability of the prevention method to ensure and maintain the accessibility in the port and the amount of additional maintenance dredging needed.
- *Operational work and Maintenance*: indicates the work and needed maintenance on the strategy when in operation.
- *Downtime and hinder*: indicates the downtime and hinder due to the applied method in the strategy.
- *(optional) Seasonality*: indicates how the strategy can take seasonality into account.
- *(optional) Safety and health*: indicates the safety and health risks of the strategy.

Resources

- *Emissions*: indicates the emissions of the measure emitted direct and indirect.
- *Resources efficiency*: indicates the number of resources needed to apply the measure.
- *(optional) Reuse*: indicates the reuse of dredged material aiming for 100% reuse.

Environmental

- *Biodiversity*: indicates the impact of the strategy on the biodiversity of the area.
- *Ecosystem change*: compares the changes in the ecosystem due to the strategy to the initial ecosystem.
- *Turbidity*: indicates the levels of turbidity caused by the measure during construction and operation.
- *(optional) Beneficial impact*: indicates the positive impact on the environment due to the strategy.
- *(optional) Species X*: indicates if the measure takes the habitat of the protective species X into account.
- *(optional) Air quality*: compares if the air quality is increased or decreased due to the new strategy.
- *(optional) Natura 2000*: indicates if the strategy takes the natura 2000 area into account in the surrounding area of the port.
- *(optional) Water quality*: compares if the water quality in the port area is improved due to the new strategy.

Community

- *Jobs*: indicates the increase in jobs due to the new strategy.
- *Impact*: indicates the positive impact on the community due to the measure.
- *(optional) Erosion*: indicates how the measure takes the occurring erosion problems in the area into account.
- *(optional) Noise*: compares if the disturbance due to noise is increased due to the strategy.
- *(optional) Innovation*: indicates if the measure promotes innovation for the port.
- *(optional) Surroundings*: indicates the interaction of the measure with the surrounding area and activities, negative or positive.

Durability

- *(optional) Lifespan*: indicates the expected efficient lifespan of the strategy.
- *(optional) Upscale*: indicates the potential to upscale the strategy easily for future port expansion.

RESOURCES			
performance indicator The dredged material is **reused**	*LOW - 1* minimal reuse of dredged material	*MEDIUM - 2* active reuse of dredged material	*HIGH - 3* large amount of reuse nearly 100%
COMMUNITY			
performance indicator The strategy provides new **jobs** for the local community	*LOW - 1* no new jobs are created	*MEDIUM - 2* several new jobs are created	*HIGH - 3* various new jobs are created and more to come

Table 3.2: Performance indicators *reuse* and *jobs* with scoring criteria

All the different performance indicators are scored form 1 to 3 for each potential strategy in the assessment sheet of the decision-making tool. An overview of the assessment sheet is given in Figure 3.4. The score indicates 1 for low performance, 2 for medium performance and 3 for high performance of the indicator. In table 3.2 two examples of indicators and their scoring criteria are given. By scoring all the selected performance indicators a score for each strategy is obtained. This score gives insight into the potential of each strategy to manage the sediment in the port.

If the stakeholders ask for added value to specific indicators, importance factors can be included in the assessment. This gives the possibility to assess the different strategies on specific performance indicators or categories, such as environmental impact, cost, or impact on the local community. In the tool, the total score per category and the total overall score are indicated. The total overall score differentiates the potential strategies from most potential to least potential. This result supports the decision for the best sediment management strategy for the port.

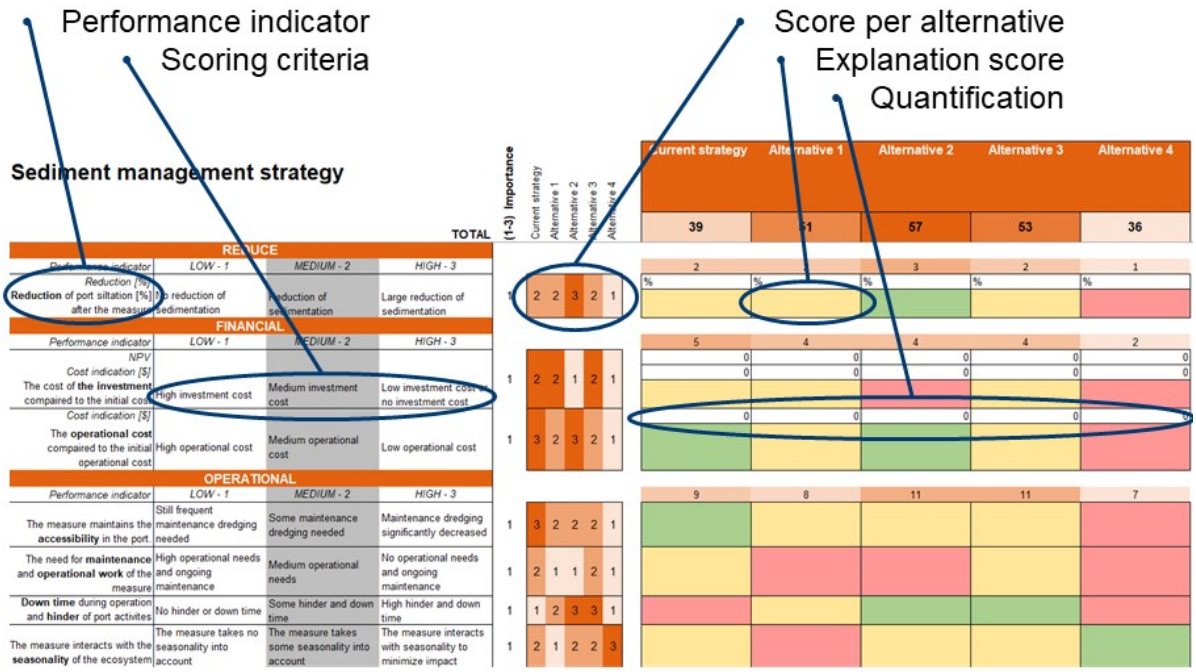


Figure 3.4: The assessment sheet of the decision-making tool, in this screen snip the elements of the assessment are indicated. The various elements are; performance indicators, scoring criteria, score per alternative, explanation of the score and quantification.

3.4.2. Effectiveness

The effectiveness of the sediment management method brings uncertainty in the results of assessment. The ten prevention measure have great potential to optimize sediment management, but the effectiveness of the measure in the specific coastal system can be uncertain. In the tool this uncertainty is considered with a %-score for the effectiveness of the strategy. This %-score is weighted over the total score to compare the strategy with this uncertainty included. If the effectiveness is estimated 80% the total score is weighted 80%, reducing the initial score.

3.4.3. Quantification

The availability of information determines the assessment's detail and identifies the possibility of quantification of performance indicators. Most of the performance indicators can be quantified if enough information is available and when this is desired for the level of detail of the assessment. Monitoring studies, area surveys, and practical examples can be applied to gather sufficient and enough available data for quantification. Examples of quantification units for various performance indicators are; *Reduction* in $\%$, *Investment cost* in $\$$, *Turbidity* in mg/l, *Downtime* in $hours$, *Emissions* in tCO_2, *Jobs* in FTE, and *Durability* in $years$. It is, however, important to consider for each individual project which performance indicators to quantify based on the available data and usage purpose of the tool.

3.4.4. Stability and sensitivity analysis

In the sensitivity analysis, the strategies are assessed with weight factors (between 0% and 100%) per category. Varying the weight gives information about the most reliable strategy for sediment management in the port. The weight factors are varied per category to indicate the stability and sensitivity of the scores. The results of the analysis indicate percentages of highest scoring strategies within all the possible combinations of varying weight factors. The stability and sensitivity both analyse the scores with different step size and bandwidth:

- *Stability*: the stability analysis indicates the variability in the results of the scores by varying the weight factors with a step size of 10%. For all the combinations possible, the highest score is determined indicating the stability of the score.
- *Sensitivity*: the sensitivity analysis indicates the variability in the results of the scores by varying the weight factors within a bandwidth of 35% of the original weight and a step size of 5%. For all the possible combinations, the highest score is determined indicating the sensitivity of the score.

It is also possible to analyse the score's sensitivity with a focus, high weight-%, on one of the categories. This is interesting if, for example, the environmental impact is considered very important. In this case, a high weight factor is indicated for the environmental category, and the analysis is carried out. The results will give insight into the best performing strategy and sensitivity with a focus on the environmental performance indicators, the environmental impact of the strategy.

3.5. Application of the strategy

In the last step, *application of the strategy*, the proposed strategy is assessed with the sediment management objectives defined in the first step. The proposed strategy should be the best fit for the port in consideration and meet the strategic objective: *improve the sediment management strategy in the port in a sustainable way and obtain a long-term solution*. To analyse if the sediment management objectives are met the weights per category in the sensitivity analysis can be varied according to the objectives. If the objectives are met, the strategy should be applied in the port's strategy and sediment management for the coming years. The next step will focus on the implementation of the strategy. The implementation phase of the strategy is not considered in the scope of this research.

3.6. Application of the decision-making approach

The decision-making approach and decision support tool can be applied to every port in the world. This approach is developed to optimize the sediment management strategy for an existing port. The decision-making approach is developed to consider the current state, the port characteristics and stakeholder interests. When starting with a case study, it is important first to understand the case and identify the problem. This will be the basis for the decision-making approach towards optimization of the sediment management strategy. From this, the objectives can be defined, followed by the steps; *2 - fit to case*, *3 - assessment of potential strategies*, and *4 - application of the strategy*. Required information and interesting aspects for the decision-making approach for an efficient application of the approach and tool are summarized below.

Coastal morphology: gives information about the hydrodynamics in the port and the coastal morphology in the area around the port.
- Wave climate
- Tide and tidal currents
- Bathymetry
- Coastal changes before and after construction of the port

Sediment balance: gives information about the sediment balance in the port area.
- Sediment source
- Sediment properties
- Sediment transport rates
- Sediment transport mode
- Sediment patterns
- Accumulation rates
- Erosion rates

Port operations: gives insight into the port operations, growth and required water infrastructure for efficient port operations.
- Major port activities
- Transport capacity
- Port finances
- Port infrastructure
- Port operators
- History of the port

Stakeholders: a stakeholder analysis provides insight into the stakeholder interests, needed requirements, and importance of certain indicators.
- Primary stakeholders: port authority, consultant, dredging company, legal and political involvement, and environmental expert.
- Secondary stakeholders: local community, local companies, entrepreneurs along the coast, NGOs, and fishing industry.

Environment: gives insight into the local ecosystem and environmental impact of the port.
- Environment components: biodiversity, marine species, fish, coastal vegetation, and marine flora.
- Environmental aspects: air quality, water quality, bottom pollution, contamination, and turbidity.
- Environment impact: during construction, operation and maintenance.

Sediment management strategy: explains the current strategy to ensure a good navigable port.
- Current maintenance and sediment management strategy.
- Main objective for optimize sediment management strategy.
- Important and notable changes in the sediment balance in the past years.

The proposed decision-making approach will support the optimization of sediment management strategies for ports. A sustainable sediment management strategy can be obtained by following the steps of the approach. The adaptive characteristic of the approach makes it possible to adjust the approach for each unique port and growth with the port project. This makes it possible to apply the decision-making approach and decision support tool to every port in the world. In the following chapter the proposed decision-making approach is used in a case study to find a sediment management strategy for Porto Amboim and understand how to apply the approach and tool.

4

Case study

In this chapter, *case study*, the decision-making approach towards a sustainable sediment management strategy is used to find a suitable strategy for a specific port. In consultation with Arcadis, a suitable case study that meets all the requirements is found. The conditions required were: enough information about the case, a port in need of more sustainable sediment management, and a good understanding of the area of interest. For the case study, the sedimentation problem in the port of Porto Amboim in Angola is used, because it matches the requirements.

4.1. Porto Amboim

Porto Amboim is located in the Kwanza Sul province along the Angolan west coast (Figure 4.1) and has around 65000 inhabitants. The port contributes to the offshore industry in the region with training programs and employment. Other economic activities in the region are fishing, livestock farming, and the agriculture of traditional crops like maize, cassava, and sweet potato. Along the coast, there is some tourism at the beaches.

Figure 4.1: Overview Porto Amboim area

4.1.1. Port operations

The port operates mainly for offshore activities and logistics, an offshore port. The construction of the port started in 2008 and was concluded in 2013. Two parties are operating in the port and involved in its infrastructure. One of the parties in the port is PAENAL. The PAENAL yard is a fabrication yard in Porto Amboim. The PAENAL yard is a Joint Venture between Sonangol (40%), SBM (30%), and DSME (30%). Sonangol operates the Marine Oil Terminal (MOT) in the port. Sonangol is a state-owned oil company and responsible for the management of oil and natural gas exploration on continental shelf of Angola. The MOT is an important terminal for Sonangol and needs to operational.

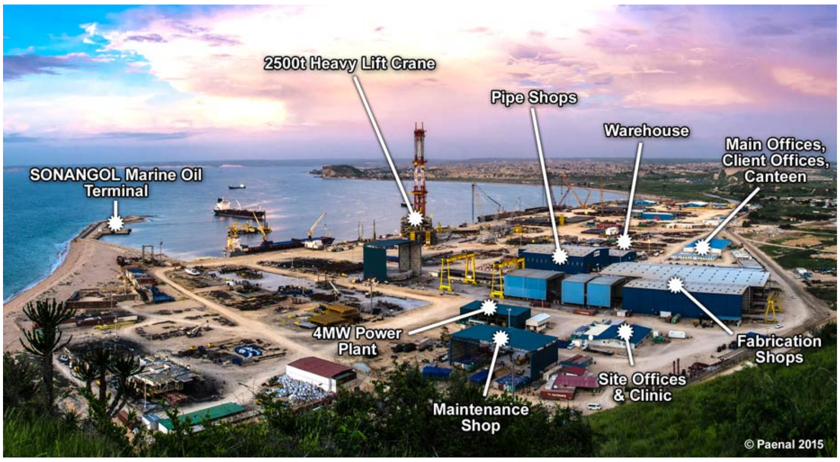


Figure 4.2: Porto Amboim: PAENAL yard overview (www.paenal-yard.com)

PAENAL sees itself committing successful technical complex projects, strong involvement of Nationals in its personnel and social responsibility in the Kwanza Sul region. An overview of the port is given in Figure 4.2. This is achieved with the values of Integrity, Respect, Excellency, and Honesty. The yard is mostly used to construct offshore equipment on fabricates on full capacity up to 10,000 tons of modules per year with a fully trained staff of 1000 employees. To maintain sufficient port operations, the depth in the port basin remains approximately constant at a depth of -11 m+LAT.

The second party is Heerema Porto Amboim (HPA), a joint venture between Heerema Marine Contractors and Cenbir. They aim to be the offshore engineering, procurement, and construction (EPC) contractor within this port. The focus lies on clients in the oil & gas and energy-related markets offering subsea services and operating a fabrication yard specialising in the construction of subsea structures. An announcement by Heerema (6 November 2020) stated that: ”The ongoing poor market conditions and sustained low oil price mean the Heerema Angola Joint Ventures are no longer economically viable. Having explored possibilities for the future within Angola, Heerema has concluded that the closure of the Heerema Porto Amboim (HPA) and Heerema Marine -Sociedade Angolana de Transportes (HMT) is the appropriate option.”

4.1.2. Stakeholders

The most important stakeholders involved in the port and their major interest are listed below. Their needs and interest will be taken into account in further developing the sediment management strategy and defining the objectives for the strategy.

- PEANAL - Sufficient port operations and profitable port
- Sonangol - An operating MOT
- Heerema Porto Ambiom - Sufficient port operations and profitable port
- City of Porto Ambiom - Maintenance of the beaches
- Port Office of Porto Amboim - Sufficient port operations and minimal maintenance
- Local enterperneurs - A profitable port or maintained beaches
- Local community - Maintained beaches and minimal impact on the community
- Fishermen - Minimal impact on the fish population
- Environmental interest group - Minimal impact on the environment

4.1.3. Environment

The environmental impact assessments (EIA) by Chance and Jean (2007) and SOAPRO and PROCESL (2009) on the area give some information on the impact of the port project on the environment, marine fauna society. The region of the port experiences two main seasons, the warm season (October to April), with an average temperature of 26°C and frequent showers and thunderstorms, and the dry season (May to September) with temperatures around 21°C.

Marine Fauna analysis observes the fish, sea birds, benthic communities, and sea turtles. The Angolan coast is an area of high marine biodiversity due to the influence of three major currents in the coastal zone. The EIA is obtained from sampling in the area that the inhabitants are typical shallow coastal water fish. The fish have mainly a commercial value, because the artisanal fishery has an important role in the area of Porto Amboim. The fishery is responsible for the employment of about 800 fishermen and therefore important for the population of the municipality. There are also some semi-industrial and industrial fleets active in the area. Another species living along the Angolan coast is the sea turtle. According to a study conducted between 2000 and 2006, three species nest in and around this area. When the port was constructed, there were no nesting places on the site, but beaches can still be used for nesting purposes. Sea turtles are endangered and vulnerable species. Their habitat is therefore important to consider.

Impact on the environment during the operational phase occurs in several ways. Contamination of the water occurs due to spills of oil or fuel from the MOT or ships. This leads to a negative impact on the marine flora and fauna, varying according to the spill's size. This highest impact is suspected during a maritime collision due to the high risk of large amounts of contamination of the water bring the fish fauna and sea turtles at high risks.

During the dredging operations in the port, sediment will occur in the water column. The suspended sediment has some influences on the fish fauna but will be low because dredging is not required frequently. Pollution of the beaches will influence the sea turtle population. The beaches are important nesting areas and need to be protected and clean for the turtles to nest. Coastal erosion also has a negative impact on nesting areas. Monitoring the fish fauna and nesting areas is essential to sustain these habitats and something to consider in the sediment management strategy.

4.1.4. Coastal morphology

A good understanding of the coastal system in the region is important, because it plays a crucial role in sediment management. The offshore swell waves that approach the Porto Amboim coast are dominantly south-southwest orientated (Figure 4.3), with a maximum record wave height of 4.5m and peak wave periods for waves larger than 4m range between 10s and 18s. As the shore normal south of the headland is 235°N and the dominant wave direction is 232°N, the waves approach the coast almost shore normal. The offshore waves change direction, propagating further into the Bay of Amboim. The headland, a sudden change in the coastline, influences the offshore wave direction. North of the headland, the offshore waves propagate into the bay. Due to diffraction around the headland, waves propagate more westerly orientated into the bay. Refraction in the shallower areas near the shore changes the wave direction further into the Bay of Amboim. The bathymetry chart, Figure 4.4, indicates the shallower areas near the shore and the headland (darker in colour). In these shallower areas refraction towards the coast occurs, changing the wave pattern and direction.

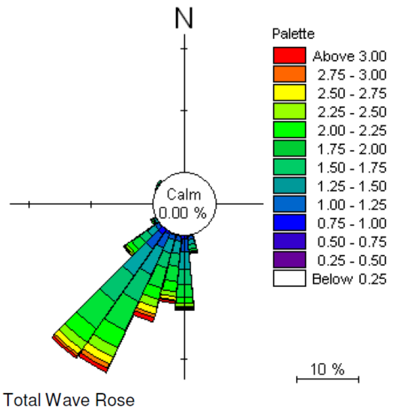


Figure 4.3: Total offshore wave rose, waves predominantly from the south-southwest

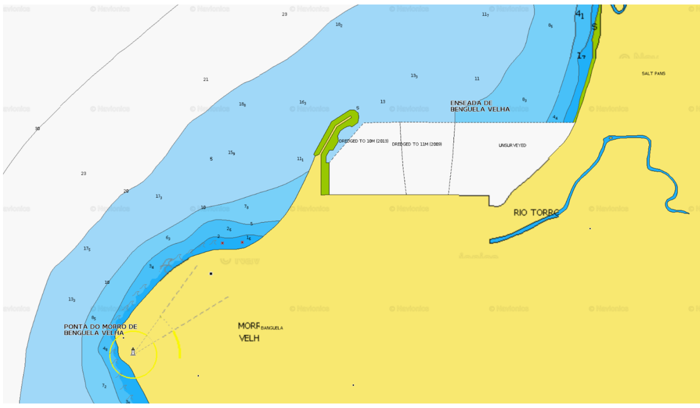


Figure 4.4: Bathymetry Porto Amboim (Navionics ChartViewer (2021))

After construction of the port

The diffraction and refraction cause waves to curb around the headland into the Bay of Amboim. After the construction of the port, further changes in the wave patterns occurred. The construction of the breakwater resulted in another sudden change in the coastline. Near the port's breakwater, as can be observed in Figures 4.5 and 4.6, the waves further diffract towards the coast, changing the wave direction. The refraction occurs in the shallow area along the west side of the breakwater and around the breakwater head. The waves near the breakwater approaching the coast predominantly from the west as indicated in Figure 4.6.

Behind the breakwater, a sheltered area is created, because the breakwater nearly blocks all incoming waves. Some waves enter this sheltered zone due to diffraction around the breakwater head and refraction on the accumulated sediments (see Figure 4.6). Due to the diffraction, the wave height of these waves propagating into the port decreases. This results in small waves height in the port behind the breakwater. North of the breakwater and the port, the waves propagate further into the Bay of Amboim. These waves propagate into the bay predominantly from the southwest and west.

Figure 4.5: Wave patterns near the port's breakwater; diffraction and refraction

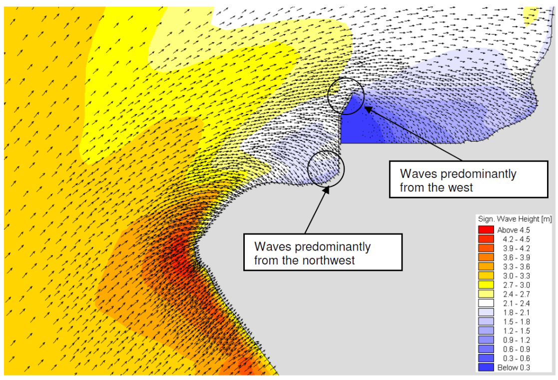


Figure 4.6: Wave patterns Porto Amboim; diffraction and refraction (Scott Wilson ,2009)

4.1.5. Sediment transport

The south-southwest waves drive alongshore sediment transport northward along the Angolan coast. Along various parts of the western coast, this northward transport is indicated and known (Mudde (2019) and Dagniaux (2013)). The sediment transport is dominantly wave-driven and occurs in the nearshore zone.

Before the construction of the port

Before the construction of the port, the sediment balance along the bay was in equilibrium. Sediment is transported along the coast and the bay of Amboim in the northward direction. The longshore transport is dominantly wave-driven and between 250,000-300,000 m^3/yr, as can be obtained from the bottom graph in Figure 4.7. The waves drive predominately a bed load sediment transport and also some suspended load sediment transport. The transport occurs mainly from the waterline to a depth of -5m MSL, in the nearshore littoral zone, as can be seen on Figure 4.7 and 4.10. Figure 4.8 gives an overview of the sediment balance of the system before the construction of the port.

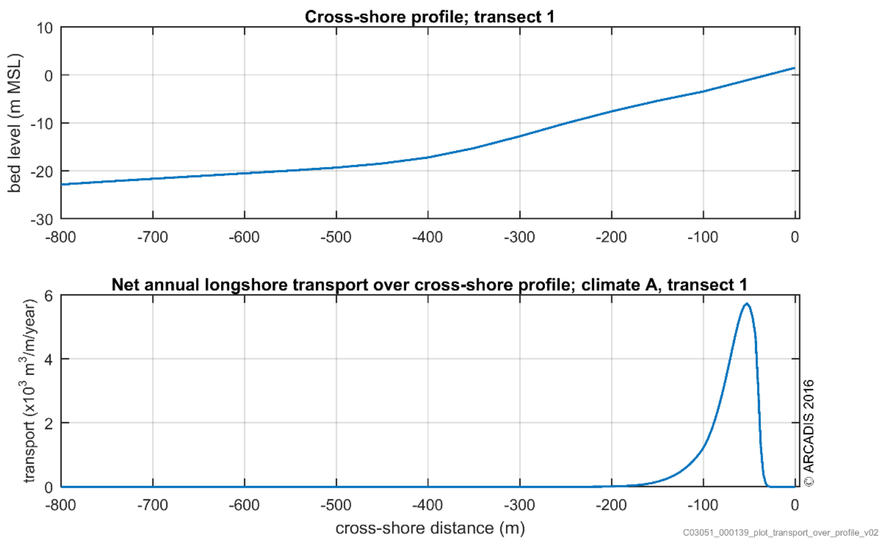


Figure 4.7: Cross-shore profile of a transect at the headland before the port and the net annual longshore transport (Arcadis, 2016)

The sediment balance (Figure 4.8) shows a wave driven sediment transport in northward direction. The transport rate is between 250,000-300,000 m^3/yr and occurs in the nearshore littoral zone. The longshore sediment transport propagates around the headland, through the bay of Amboim and along the city of Porto Amboim to the north. This transport is driven by the southwestern oriented offshore waves.

Figure 4.8: Sediment transport balance Porto Amboim before the construction of the port

Figure 4.9: Overview Porto Amboim area

After construction of the port

The construction of the port from 2009-2013 disturbed the sediment balance. In the first years, large volumes of sediment accumulated near the breakwater creating a shallow foreshore with a gentle slope on the western side of the port's breakwater, *location 1*. This blockage resulted in a decrease in northward longshore sediment transport towards the Bay of Amboim. The development of the gentle submerged bottom profile can be observed in Figure 4.10. The figure indicates the bottom profiles in 2010, 2011 and 2015 observed in transect surveys near the breakwater. A comparison of the 2010 and 2015 transect shows the developed gentle slope due to the accumulated sediment in the area near the breakwater. As this gentle slope developed and the area in front of the breakwater got filled up the longshore sediment transport rate to the north of the breakwater increased. This increase in longshore sediment transport in front of the breakwater from 2010 to 2015 respectively is also indicated in Figure 4.10.

Several years after the construction of the port, accumulation of sediment became visible at the lee side of the breakwater as well, *location 2*. At this sheltered lee side area of the breakwater, wave energy is minimum making this area perfect for sediment to accumulate, because the wave-driven sediment transport capacity decreases significantly in this area. As a result of wave diffraction around the breakwater head, sediment is transported towards this lee side of the breakwater, forming a spit into the port. The spit grew further into the port over the past few years, because sediment accumulation at the western side of the breakwater decreased from 2015. The spit continues to grow every year, because the reduced wave energy causes the sediment to settle. The surface area of the spit was in 2020 about 110,000 m^2 at the leeside of the breakwater. As the port's desired depth is -11m+LAT, the volume of the spit is approximately 1,200,000 m^2. This volume continues to grow if no sediment management measures are executed.

From the construction of the port till the port now accumulation of sediment near the breakwater continued. The yearly sedimentation rate observed in this area, first at the west side of the breakwater and later at the leeside of the breakwater, is between 130,000-180,000 m^3/yr. This yearly averaged rate is obtained from the sedimentation volumes.

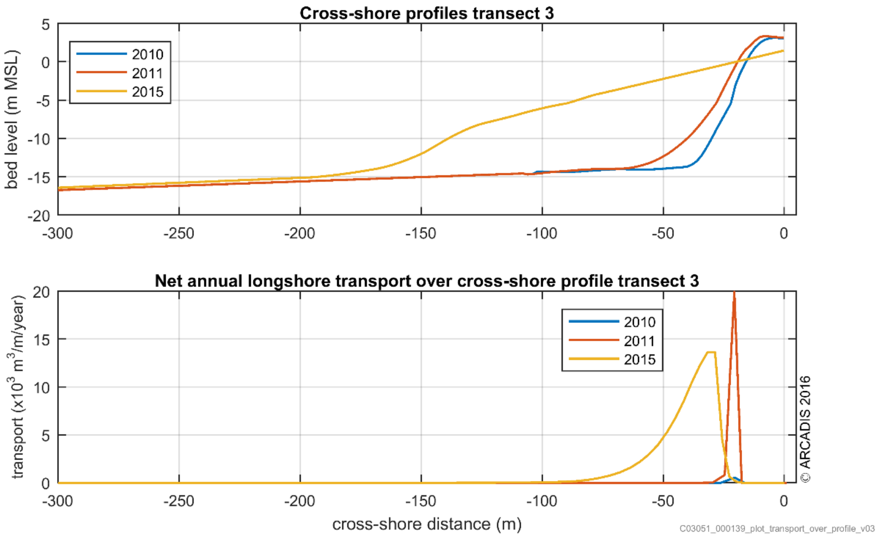


Figure 4.10: Cross-shore profiles of a transect at *location 1* for the years 2010, 2011, and 2015 and the computed net annual longshore transport for the cross-shore profiles (Arcadis, 2016)

This sedimentation rate and the blockage of sediment transport in this area reduces the northward longshore sediment transport rate to 100,000-150,000 m^3/yr. This reduction results in erosion further up north along the coast in the Bay of Amboim (*location 3*) and near the city of Porto Amboim (*location 4*), because less sediment is available in the system. The coastline changes between 2015-2020 are analysed with *CoastSat* (Vos et al., 2019) using *Google Earth Engine*. Figure 4.11 illustrates the coastline analysis of the port and Bay of Amboim and figure 4.13 illustrates the coastline analysis near the city of Porto Amboim. CoastSat detects the coastline on *Google Earth* satellite images and extracts its position. In Figures 4.11 and 4.13 a retreat of the coastline is visible. A growing spit in the years 2015-2020 can be observed from Figure 4.11.

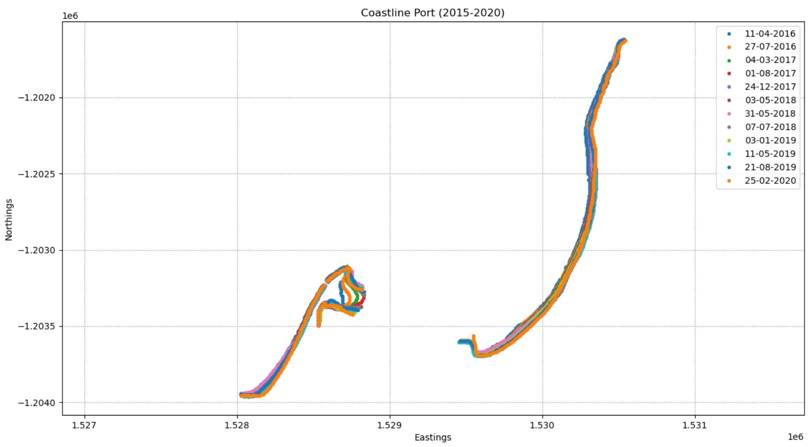


Figure 4.11: CoastSat analysis - spit and coastline position in the port area (2015-2020)

The erosion in the Bay of Amboim, *location 3*, is caused by the decrease in available sediment in the system and the relocation of the diffraction point in the bay. Before the construction of the port, the bay was in a dynamic equilibrium with a wave diffraction point around the southwestern headland. Due to the construction of the port breakwater, the diffraction point influencing the shape of the bay shifted to the head of the breakwater. This new diffraction point influences the bay shape aiming to obtain a new equilibrium crenulate shape. This process towards a new bay shape equilibrium also influences the coastline orientation and can be a cause of the coastline retreat in the bay. With the parabolic bay shape equation, an expected coastline orientation and position is indicated and can be observed in

Figure 4.12. As not all the sediment is blocked by the port, the bay will find a new dynamic equilibrium close to the Static Equilibrium Planform (SEP).

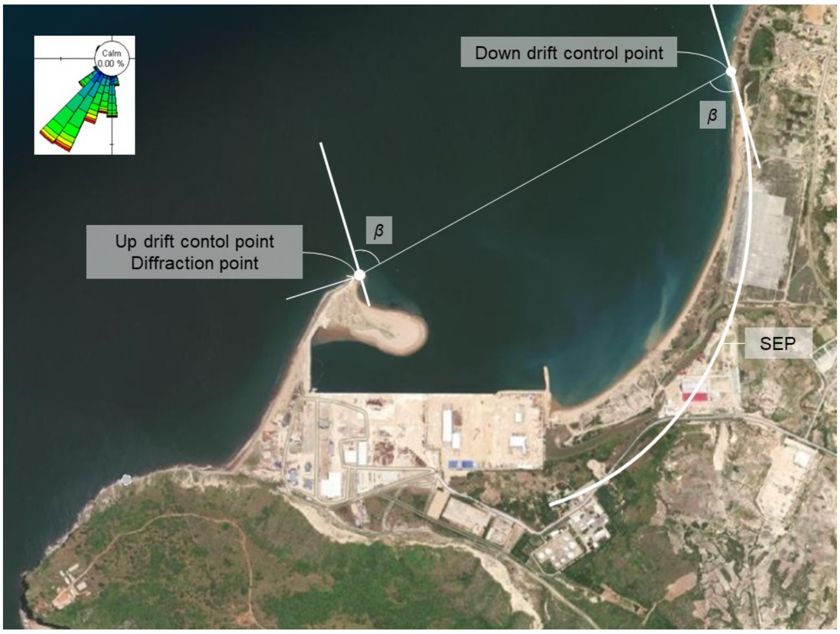


Figure 4.12: Indication of the Static Equilibrium Planform (SEP) of the Bay of Amboim

The erosion further up north near the city of Porto Amboim, *location 4*, is illustrated in Figure 4.13. The cause of this erosion is the decrease in available sediment in the system due to the trapping of sediment in the port. In the figure and from *Google Earth* is observed that retreat of the coastline first occurred along the southwestern part of the coastline. In 2018 coastline strengthening measures are taken in the southwestern part of the coastline. These measures help to stabilize the coastline in this part of the coast, trapping sediment coming from the south. Due to these measures, erosion more up north increased, and a significant retreat of the coastline is observed in this area. This erosion will continue if no countermeasures are taken due to the decreased available sediment in the system.

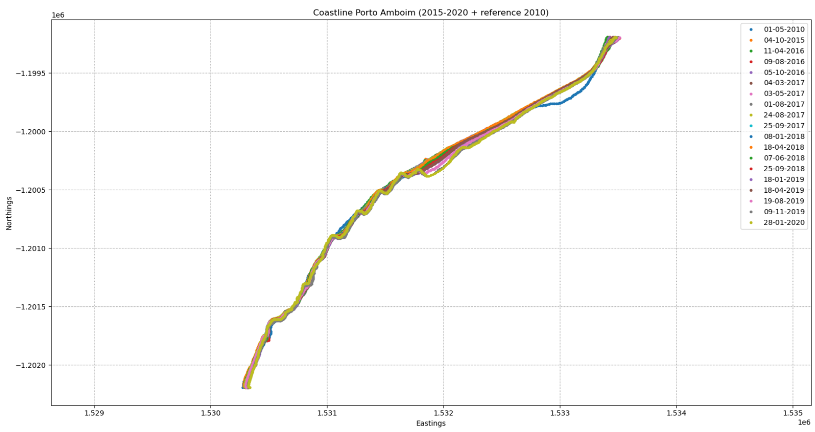


Figure 4.13: CoastSat analysis - coastline position Porto Amboim (2015-2020 + 2010)

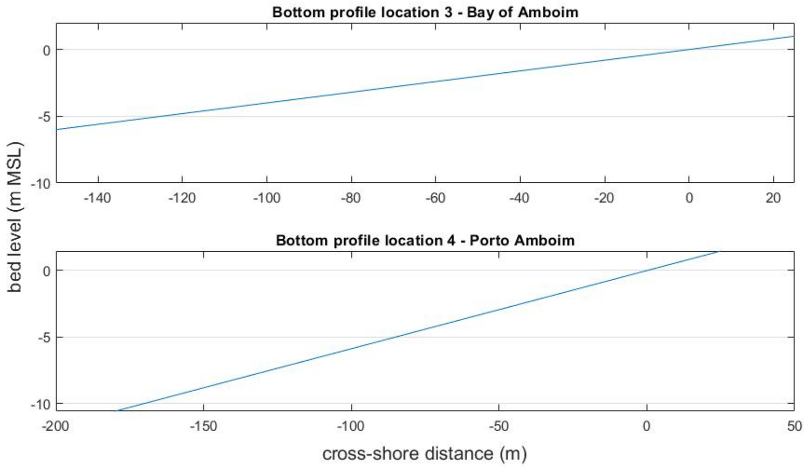


Figure 4.14: Indication of the cross-shore profiles at *location 3* and *location 4*

The sedimentation and erosion rates over the years (2011-2020) are summarized in Table 4.1. These amounts are obtained from coastline analysis with *Google Earth*, the cross-shore profiles in the area (Figure 4.14), and from the available data and information from the *Arcadis project*. The yearly averaged wave-driven longshore sediment transport rate in this region is 250,000 - 300,000 m^3/yr. From the table can be obtained that this sediment transport is partially blocked by the sediment trapping effect of the port. This sedimentation rate is around 130,000-180,000 m^3/yr. This results in a decrease in available sediment in the system further up north. This decrease is one of the causes of the erosion further up north along the coast. The erosion rate varies between 120,000-190,000 m^3/yr. From these yearly averaged rates can be concluded that this coastline near the port, in the bay and near the city is still not in equilibrium and dynamically changing every year, an overview of the sediment balance is given in Figure 4.15. Optimizing sediment management will help the system to find a dynamic equilibrium again.

	Sedimentation		Erosion	
year	location 1 *breakwater*	location 2 *lee side port*	location 3 *Bay of Amboim*	location 4 *Porto Amboim*
2011	+ 140,000 m^3	+ 20,000 m^3	- 80,000 m^3	- 40,000 m^3
2012	+ 140,000 m^3	+ 20,000 m^3	- 100,000 m^3	- 50,000 m^3
2013	+ 140,000 m^3	+ 50,000 m^3	- 100,000 m^3	- 60,000 m^3
2014	+ 50,000 m^3	+ 90,000 m^3	- 100,000 m^3	- 50,000 m^3
2015	+ 30,000 m^3	+ 120,000 m^3	- 100,000 m^3	- 40,000 m^3
2016	+ 10,000 m^3	+ 150,000 m^3	- 110,000 m^3	- 50,000 m^3
2017	-	+ 160,000 m^3	- 90,000 m^3	- 80,000 m^3
2018	-	+ 180,000 m^3	- 90,000 m^3	- 100,000 m^3
2019	-	+ 190,000 m^3	- 80,000 m^3	- 100,000 m^3
2020	-	+ 180,000 m^3	- 80,000 m^3	- 100,000 m^3
total	+ 510,000 m^3	+ 1,160,000 m^3	- 930,000 m^3	- 670,000 m^3

Table 4.1: Yearly sediment increase and decrease at the four locations in the port (2011-2020)

Sedimentation in the port area is inevitable, because the conditions in the port are suitable for the sediment to accumulate. First sedimentation at the west side occurred. Once this area was filled, the sediment continued up north and accumulated in at the leeside of the breakwater. The blockage of the longshore sediment transport due to the port in this area causes a decrease in available sediment in the system. This decrease resulted in erosion further up north in the Porto Amboim area. Figure 4.15 gives an overview of the sediment transport balance. A sediment management strategy needs to be found to accurately manage the sediment in the Porto Amboim area and bring the system back into equilibrium.

Figure 4.15: Sediment transport balance Porto Amboim after the construction of the port.

4.1.6. Sediment management strategy

Currently, there is no strategy to manage sediment in the port area. As indicated in the previous section, there are sediment problems in this area. A spit continues to develop into the port and Bay of Amboim and erosion continues near the city of Porto Amboim. A new strategy needs to be developed to optimize sediment management.

Future perspective with no measures

If no measures are taken in the area, the port will be no longer operational due to navigation problems. Spit development occurs more often along the Angolan coast, as can be obtained in the studies on the Lobito (Mudde, 2019) and Luanda (Dagniaux, 2013) coast. From the studies can be learned that if now measures are taken spit development will continue into the port. The spit development along these parts of the coast is driven by a longshore sediment transport directed northward driven by SW to SSW waves. The accumulation near the Luanda spits influences the sediment budget, resulting in erosion at the upstream side. Sediment management is needed in this region to meet the area's demands and to deal with these eroding coastline sections. To avoid erosion the Lobito spit is managed with groynes along the coast and frequently monitored to meet the area demands. From these case studies can be concluded that accurate sediment management is required to counteract the spit formation and make the port operable again. The erosion problems near the city of Porto Amboim underpin this need, because these problems will further continue if no sediment management measures are taken any time soon.

New sediment management strategy

As can be concluded from the coastal system analysis, the following requirements are needed to satisfy the annual sediment management. The sediment management strategy should satisfy the following main requirements:

- The strategy should manage the sedimentation problems and restore the sediment balance in the area.
- The strategy should contribute to efficient port operations.
- The strategy should prevent further coastal erosion north of the port near Porto Amboim by placing the dredged material down-drift.

Additionally, every sediment management strategy needs to take the spit removal in the port into account. The spit now hinders and blocks the port entrance and the Marine Oil Terminal (MOT) influencing the workability in the port. The strategy needs to consider the removal of the total volume of the spit of $1,200,000m^3$.

The main conclusion that can be drawn on the case study and that will be used to create relevant sediment management strategies are summarized below.

- The waves are predominately from the south-southwest, with a maximum record wave height of $4.5m$ and peak wave periods for waves larger than 4m range between $10s$ and $18s$.
- A small wave component comes from the northwest, with significant wave height up to 1m.
- The offshore wave diffract around the headland and refract near the breakwater approaching the southern part from the northwest.
- The waves approach the tip of the breakwater predominantly from the west.
- The waves diffract around the breakwater tip and refract towards the spit at the lee side of the breakwater.
- The yearly sediment transport rate is 250,000-300,000 m^3/yr in a northward direction.
- The yearly sedimentation rate near the breakwater and at the lee side of the breakwater is in about 130,000-180,000 m^3/yr.
- The waves distribute the sediment northward of the port along the coast of Porto Amboim.
- The median sediment diameter D_{50} is $450\mu m$.

4.2. Sediment management objectives

In this section the decision-making approach for the sediment management strategy is applied for the case study, Porto Amboim. The focus and boundary conditions are determined by the case study characteristics and stakeholders' needs. With the information on the case study and the stakeholders' needs, the sediment management strategy's objectives can be defined, *step 1* of the approach. The main objective to obtain with the sediment management strategy is:

> *Strategic objective*: Improve the sediment management strategy in the port in a sustainable way and obtain a long-term solution.

To obtain this main objective, the following case-specific objectives are defined. With these objectives, the optimal sediment strategy for Porto Amboim can be found.

- The sediment management strategy manages the sediment in the port into its natural northward direction.
- The sediment management strategy maintains the navigability in the port for efficient and effective port operations.
- The sediment management strategy is cost-efficient.
- The sediment management strategy has minimal impact on the environment.
- The sediment management strategy counteracts the erosion along the coast and restores the sediment balance.
- The sediment management strategy has a positive impact on the community of Porto Amboim.
- The sediment management strategy has a 20 year lifetime.

4.3. Fit to case

In the pre-assessment, *step 2 - fit to case*, the suitability of the ten different prevention methods is assessed. An overview of the pre-assessment is given in Table 4.2. The assessment resulted in four suitable prevention measures having the potential for sustainable sediment management in this case study. With these prevention measures, the four potential strategies will be worked out in more detail.

	Suitable	Reasoning
Sediment trap	yes	interesting to create at the port entrance
Sediment bypass system	yes	interesting to install in the port
Habitat creation	no	no suitable area for this method
Blocking structure	yes	interesting to apply on the beach near the port
Blocking screen	no	no small entrance not suitable for a screen
Guiding structure	no	no high current velocities to stimulate
Natural sediment bypass	yes	possible to stimulate at breakwater head
Resuspension of sediment	no	no fine sediment and high current velocities
Fluid mud	no	no fine sediment in the area
Bed levelling	no	no specific basin area interesting to use this method

Table 4.2: Pre-assessment of prevention methods suitable for sediment management in Porto Amboim

The four suitable prevention measures are applied to the case study area resulting in the following sediment management strategies. Each strategy aims to meet the objectives optimizing the sediment management strategy. The main purpose is to manage and restore the sediment balance and the yearly sedimentation rate of 130,000-180,000 m^3/yr for a lifetime of at least 20 years. The spit removal should be included in the strategy as well. For a complete assessment, two dredging approaches are also considered in the assessment, dredging with own equipment and dredging with a contractor. In this section, the four different strategies are explained in detail.

Dredging with own equipment

One possible way to carry out the maintenance dredging is to use own equipment for the dredging works. For the project requirements, it is possible to use a relatively small dredger operating more frequently during the year, because the needed dredging capacity is around $180,000 m^3/yr$. An example of a suitable dredger is the Damen DOP dredger (Figure 4.16) equipped with a plain suction head with a jet water system and a heave compensator to enable the vessel to work in waves up to $2m$, making this dredge suitable for this area. The dredger equipment is mounted on a pontoon which can be positioned with a workboat to the dredging location. During operations, the accumulated sediment is dredged with the suction head and the dredged material is pumped to the pontoon and discharged via a floating pipeline of $1km$. The discharge point will be positioned at the downstream site of the port to restore the sediment balance in the area. The cost of the dredge, its equipment, and the pipeline are approximately $\$2,500,000 - \$3,500,000$. The lifetime of the dredger is in the order of 15-20 years. Operating own equipment asks for high demands for spares, maintenance, and staffing, making it an interesting opportunity for the community, but it also brings sediment management responsibility.

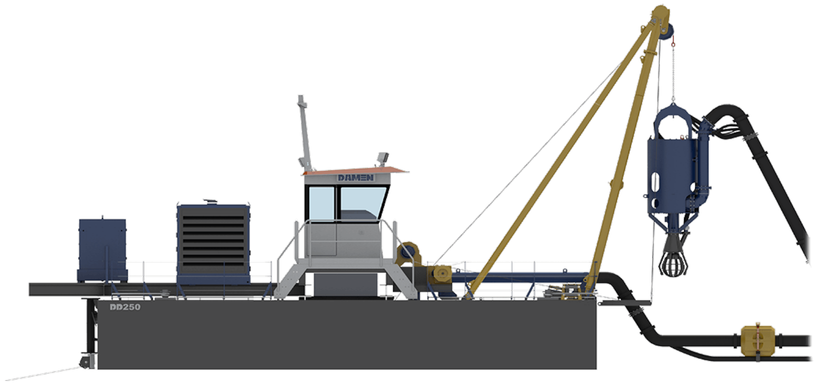


Figure 4.16: DOP dredger (products.damen.com, 2021)

Maintenance dredging with contractor
To obtain an optimal sediment management strategy the prevention measures are often combined with maintenance dredging. Various dredging contractors can be used to carry out the maintenance dredging works for the port. In this area international or local contractors are available to conduct the dredging works. The main requirements for every strategy are that the contractor:

- Dredges the accumulated sediment, sand
- Is able to operate in swell waves approaching the breakwater
- Deposits the dredged material $2 - 2.5km$ up north in the Bay of Amboim to manage the erosion

A standard equipment type meeting these requirements is the Trailing Suction Hopper Dredger (TSHD). The cost for the dredging operations are based on the mobilisation and demobilisation cost for the contractor and the unit cost for dredging ($\$/m^3$). For this maintenance dredging an (inter)national contractor needs to be found being responsible for the maintenance dredging works for the coming 20 years.

The four potential prevention measures are combined with dredging techniques and worked out in more detail to four potential sediment management strategies. These potential strategies are described in more detail in the following subsections.

4.3.1. Sediment trap

The prevention method used in this strategy is the sediment trap. The sediment trap traps the sediment before entering the port area and stores the sediment in this location till a new dredging campaign. The sediment can be managed efficiently with the sediment trap and regular maintenance dredging. It is difficult to predict the exact trapping efficiency of a sediment trap, but a good estimation can be made with an understanding of the sediment transport patterns in the area. A more detailed description of the workability of this measure can be found in the appendix, A.1. The aspects to consider for this sediment management strategy are sedimentation rate near and in the trap, length and depth of the trap, and ability to dredge in the specific area.

Figure 4.17: Strategy 1 - Sediment trap

Working principle
The sediment trap aims to reduce the sedimentation rate near the head and lee side of the breakwater, to function as a buffer zone for the sediment to accumulate. To obtain this, the trap is located around the breakwater head with a buffer capacity of $250,000 - 360,000m^3$. With this capacity the trap is suitable to trap the sediment for at least two years before filled up. The trap is partly located at the northward side of the breakwater head, the exposed site (see Figure 4.17). At this location, the trap reduces the sedimentation rate in the port, because the dredged trench reduces flow velocities in the above water column and decreases the capacity to transport sediment. This results in sediment accumulation in the trap. The refraction around the breakwater head will also be reduced, because the shallow foreshore, causing the refraction, is removed during the construction of the trap. This reduction will decrease the sediment transport into the port, because this transport is mainly driven by the diffracted and refracted waves. The other part of the trap is located at the lee side of the breakwater. At this location, the trap stores the accumulating sediment in the sheltered zone. Meeting the working principles, the traps contribute to the port's sediment management in combination with maintenance dredging every one or two years.

Strategy 1a - Sediment trap and own equipment
Considering all the requirements described above leads to a sediment management strategy for the Porto Amboim. In the first phase of this strategy, the spit needs to be removed, and the traps need to be dredged. This results in a large dredging campaign in the first phase of this strategy for which a contractor needs to be involved. A total volume of $1,200,000m^3 + 250,000m^3 = 1,450,000m^3$ needs to be dredged in this first campaign to make the port operational again and construct the traps. The dredged material obtained during this campaign is deposit at the northward side of the port to nourish the erosion in the Bay of Ambiom and further up north near Porto Amboim, restoring the sediment balance in the system. The next step is the purchase of the DOP dredge for all the maintenance dredging works. During the year ongoing maintenance is included in this strategy with drag barring to move sediment from the port area into the traps. This measure is carried out by the port authority as well. To obtain a long-term sediment management strategy, the traps need to be dredged continuously every one to 1.5 years with the DOP. During this campaign, a volume of approximately $180,000 - 270,000m^3$ needs to be dredged in the port and traps. Monitoring the sediment patterns and sedimentation over the years will tell more about the efficiency of the traps. If high efficiency is obtained, a less frequent dredging campaign can be considered, decreasing the total impact and cost.

Strategy 1b - Sediment trap and dredging contractor
In the first phase of this strategy the spit will be removed and the sediment trap needs to be dredged. The configuration of the sediment trap is indicated in Figure 4.17. A large dredging campaign will be

carried out during the construction of the trap with $1,200,000m^3$ for the spit and $360,000m^3$ for the sediment trap giving a total volume of $1,450,000m^3$ of sand to be dredge. The dredged material will be deposited in the north near Porto Amboim to restore the sediment balance and nourish the beaches in the area. To obtain a long-term sediment management strategy, the traps need to be dredged continuously every two years. During this maintenance dredging a volume of approximately $360,000m^3$ needs to be dredged in the port and traps. Monitoring the sediment patterns and sedimentation over the years will tell more about the efficiency of the traps. If high efficiency is obtained, a less frequent dredging campaign can be considered, decreasing the total impact and cost. If the trapping efficiency is not sufficient drag barring can be considered in the strategy and used for more frequent maintenance.

strategy	1a. Sediment trap & own equipment	1b. Sediment trap & dredging contractor
capacity trap	250,000 m^3	360,000 m^3
maintenance	drag barring	optional drag barring
dredging	own equipment	contractor
frequency	every year to 1.5 year	every two years
amount	180,000 - 270,000 m^3	360,000 m^3
depositing	along the coast up north	near city of Porto Amboim

Table 4.3: Overview working principles sediment trap strategies

4.3.2. Sediment bypass system

The sediment bypass system captures the sediment at the up-drift side port. The captured sand is pumped to the down-drift side of the port, northward, to continue in the northward longshore transport direction. The sediment bypass system contributes to the optimization of the sediment management strategy. Aspects to consider in the sediment bypass system's design are the pumping capacity, the intake location, the discharge point, and the length of the discharge pipeline.

Figure 4.18: Strategy 2 - Sediment bypass system

Working principle

The sediment bypass system aims to capture the sand up-drift of the port and deposit the sand down-drift of the port. With the system, the sediment is managed around the port and unable to settle inside the port. To obtain this, a portable sediment bypass system with a suction head and jet pump is constructed on the head of the breakwater. At this location near the breakwater, the system will capture the accumulated sand and transport it to the other side of the port. The system is operable in the nearshore zone between 0 and $-5m$ MSL where most of the sediment transport takes place. The configuration of the system is shown in figure 4.18. A fixed pipeline and pumping system discharges the dredged sediment to the down-drift side of the port. The pumping capacity of up to $300,000m^3/yr$ manages the sediment in Porto Amboim. Operating such a system requires high maintenance and operational needs creating responsibility and work for the port and the community.

Strategy 2 - Sediment bypass system
Realizing this system creates a sediment management strategy for Porto Amboim. In the first phase, the spit needs to be removed with a dredging campaign, and the beach location for the system needs to be prepared for construction. After this, the construction of the system will follow. The sediment bypass system consists of a suction head and jet pump with a yearly pumping capacity of up to $300,000m^3$. A pipeline of approximately $2,5km$ will be constructed alongside the oil pipeline and connected to the system. The pipeline transports with pumping stations the dredged material to the north into the Bay of Amboim. After the construction, the operation of the system starts. The system manages the port's sediment flow with a pumping rate of $130,000-180,000m^3$ per year. Monitoring the sediment patterns, yearly sediment transport rate, and bypassing efficiency determine the exact amount of the pumping rate and potential need for additional maintenance dredging or other additions. An optional addition to the system will be the construction of a groyne at the lee side of the breakwater. This groyne blocks the sediment transport and captures the sediment before entering the port. This adaptive measure will create a buffer zone where sediment will be trapped and captured by the sediment bypass system to be transported away from the port. This strategy assumes that no extra maintenance dredging is needed with a good operating sediment bypass system. If all these phases are considered and complete, this sediment management strategy is interesting for Porto Amboim.

strategy	2. Sediment bypass system
pumping capacity	130,000-180,000 m^3
system	movable dredging suction system at the head of the breakwater
operational	operating system during the whole year
maintenance	of the system, pumping station and pipeline
dredging	adaptive if needed in the area
depositing	along the coast up north through pumping station and pipeline

Table 4.4: Overview working principles sediment bypass system strategy

4.3.3. Blocking structure: groynes
The construction of groynes along the breakwater will function as a blocking structure. The principle of a blocking structure is to keep the sediment out. The groyne blocks and traps the sediment before entering the port. In this area most of the sediment transport takes place. In this specific area, the sediment is stored till a new dredging campaign. The structure allows expanding the time between to dredging campaign, reducing the overall cost. The trapping capacity and accumulative characteristics of groynes can be seen at many places along the coast and is further described in the appendix, A.2. The blocking structure, trapping area, and maintenance dredging contribute to the optimization of the sediment management strategy. Aspects to consider in this method's design are the location of the blocking structure, the amount of sediment to block, and the additional need for maintenance dredging.

Working principle
The blocking structures aim to create a sediment buffer for the sediment before it enters the port, keeping the sediment out. In this buffer, the sediment can be stored between two dredging campaigns. To obtain this buffer two groynes are constructed at the south-west side of the breakwater. Figure 4.19 shows the configuration of this strategy. The groynes block the northward directed longshore sediment transport and store sediment near the breakwater in the nearshore zone. In this area the majority of the sediment transport occurs, as can be obtained from figure 4.20. The required storage capacity of the blocking structure is between 270,000-360,000 m^3. This storage capacity will be obtained with the construction of two $120m$ long groynes on the mild sloped foreshore with a slope of $1:14$ and a width of $700m$. Before the construction the area needs to be prepared for the placement structure with a dredging campaign. During the construction, the already dredged material can be used as a construction material. Meeting the working principles, the blocking structure contribute to the port's sediment management in combination with maintenance dredging.

Figure 4.19: Strategy 3 - Blocking structure: groynes

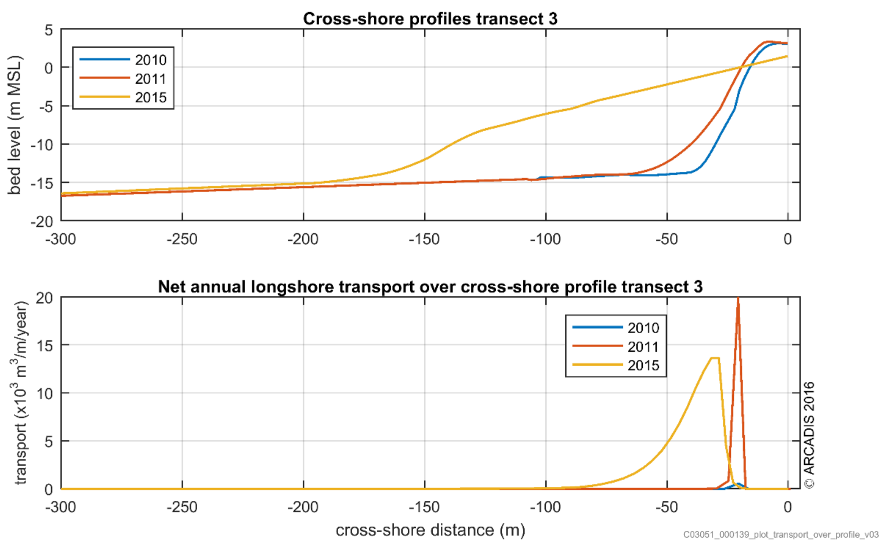


Figure 4.20: Cross-shore profiles of a transect at *location 1* for the years 2010, 2011, and 2015 and the computed net annual longshore transport for the cross-shore profiles (Arcadis 2016)

Strategy 3a - Blocking structure and own equipment

To realize this strategy first the spit needs to be removed. A contractor is included to dredge the spit and prepare the fore shore near the breakwater for the groyne construction. After that, the construction phase can start building two $120m$ long groynes along the south-west side of the breakwater at the beach. With the blocking structure in place, a buffer capacity of $270,000m^3$ on the $700m$ long beach is created. Monitoring the groynes' trapping capacity will give a good understanding and estimation about the amount to dredge during the yearly campaigns. For this yearly campaigns a DOP dredge is purchased by the port authority. The dredging will be carried out in the calm season to avoid large swell waves making it difficult for the DOP dredge to operate. During the dredging operations a dredging volume of approximately $180,000-270,000m^3$ needs to be dredged to manage the sediment balance in the area. The dredged material will be discharge further up north down-drift to restore the sediment balance and eroded areas in the north. If all these phases are considered and completed, this strategy can potentially sustain sediment management in the port.

Strategy 3b - Blocking structure and dredging contractor
Considering the working principles, a sediment management strategy with a blocking structure is assessed in combination with maintenance dredging carried out by a contractor. In the first phase, the spit needs to be removed, and the foreshore near the breakwater will be prepared for the groyne construction. After that, the construction phase can start building two $140m$ long groynes along the south-west side of the breakwater at the beach. With the blocking structure in place, a buffer capacity of $360,000m^3$ on the $700m$ long beach is created. The long-term sediment management strategy objective is obtained by a maintenance dredging campaign with a contractor every two years. The dredged material from the campaign will be placed up north near the coast of Porto Amboim to nourish the eroded areas. Monitoring the groynes' trapping capacity will give a good understanding and estimation about the amount to dredge during the campaigns. Expected is that the amount to dredged will vary between $300,000 - 360,000m^3$ dredged near the groynes and in the port every two years. If all these phases are considered and completed, this strategy can potentially sustain sediment management in the port.

strategy	3a. Blocking structure & own equipment	3b. Blocking structure & dredging contractor
construction	two groynes 120 m long	two groynes 140 m long
capacity buffer	270,000 m^3	360,000 m^3
maintenance	dredging in calm season	dredging in calm season
dredging	own equipment	contractor
frequency	every year to 1.5 year	every two years
amount	180,000 - 270,000 m^3	360,000 m^3
depositing	along the coast up north	near city of Porto Amboim

Table 4.5: Overview working principles sediment trap strategies

4.3.4. Natural sediment bypassing
Expanding the breakwater further and changing the design increases the transport capacity through the channel, stimulating natural bypassing. The bypass structure enhances the sediment transport northward along the coast into the Bay of Ambiom and reduces the amount of sediment accumulating in the port. The remaining amount of sediment accumulating in the port still needs to be managed with maintenance dredging. In the design of the natural bypassing enhancing structure, the following aspects are important to consider, the shape and length of the bypassing structure, the expected sediment patterns and flow, and the additional need for maintenance dredging. In this section to different strategies where the prevention measure natural sediment bypassing is applied are described in detail and summarized in the table 4.6 below.

Working principle
The additional expansion of the breakwater aims to improve the longshore sediment transport and to enhance natural sediment bypassing to the bay of Amboim. Contraction of the flow near the breakwater head creates a longshore current and stimulates longshore sediment transport in the northward direction. To obtain this, the existing breakwater needs to be expanded in the sediment transport direction. With this natural bypass, a part of the old sediment balance in the bay can be restored, because a part of the sediment is transported further up north. It is expected a portion of the sediment will still accumulate near the breakwater. The expected sedimentation patterns are indicated in Figures 4.23 and 4.24. The optimal sediment management is obtained in this strategy when the breakwater construction is combined with maintenance dredging near the breakwater and in the assess channel of the port. The dredged material will be deposited down-drift to restore the sediment balance in the bay further.

Strategy 4a - Natural sediment bypassing and own equipment
To realize this strategy, first the spit needs to be removed. A contractor is involved to carry out this operation. Some of the dredged material from the spit will be used to construct the berm for the breakwater extension. After the spit removal, the breakwater location needs to be prepared for construction. Followed by the construction of the breakwater with a length of $100m$ (see Figure 4.21). Frequent monitoring of the sediment patterns near the breakwater gives insight into the bypassing rate of the sediment. It is expected that the structure will manage the sediment in the long-term in combination with a maintenance dredging campaign every year. For this dredging campaign own equipment is

used. A DOP dredge is purchased for these campaigns. During this campaign, a volume of about $180,000 - 270,000m^3$ is dredged near the breakwaters, and in the access channel to the port, the exact amount will depend on the bypassing rate. The dredged material will be deposited down-drift of the port with a discharge pipeline to restore the sediment balance in the bay and further down-drift. If the natural bypassing is enhanced and sufficient this strategy will optimize the sediment management in the port.

Figure 4.21: Strategy 4a - Natural sediment bypassing short expansion

Figure 4.22: Strategy 4b - Natural sediment bypassing long expansion

Strategy 4b - Natural sediment bypassing and dredging contractor
This strategy start with the removal of the spit near the breakwater head. A part of the dredged material from the spit can be used to construct the berm for the breakwater extension. After the spit removal, the breakwater construction phase can start. The breakwater will have a length of $300m$ and northeast and easterly orientated (see Figure 4.22). Frequent monitoring of the sediment patterns near the breakwater gives insight into the bypassing and accumulation rate of the sediment. It is expected that the structure will manage the sediment in the long-term in combination with a maintenance dredging campaign every two years. During the maintenance dredging campaign the accumulated sediment near the breakwater needs to be dredged to ensure the accessibility of the port. It is expected that a volume of $360,000m^3$ needs to be dredged every two years, to obtain the required accessibility. The exact amount that needs to be dredged during the maintenance campaigns depends on the bypassing rate. The dredged material will be deposited down-drift near Porto Amboim to restore the sediment balance in this area. If the natural bypassing is enhanced and sufficient this strategy will optimize the sediment management in the port.

Figure 4.23: Strategy 4a - Natural sediment bypassing short expansion and expected sedimentation

Figure 4.24: Strategy 4b - Natural sediment bypassing long expansion and expected sedimentation

strategy	4a. Natural sediment bypassing & own equipment	4b. Natural sediment bypassing & dredging contractor
construction	breakwater extension 100 m	breakwater extension 300 m
maintenance	dredging in calm season	dredging in calm season
dredging	own equipment	contractor
frequency	every year to 1.5 year	every two years
amount	180,000 - 270,000 m^3	360,000 m^3
depositing	along the coast up north	near city of Porto Amboim

Table 4.6: Overview working principles natural bypassing strategies

These are the seven potential strategies for sediment management in Porto Amboim. Each strategy is worked out in a preliminary design to meet the objectives for the port. The decision-making tool assesses the potential strategies to find the port's most suitable strategy based on the objectives. The seven proposed strategies are assessed with the performance indicators to score the performance of each strategy and its potential for sustainable sediment management in Porto Amboim.

4.4. Assessment of potential strategies

The strategies are compared and assessed with the decision-making tool in *Microsoft Excel*, third step of the approach *assessment of potential strategies*. An overview of the assessment sheet is given in Figure 4.25. This section describes the assessment of the strategies for Porto Amboim and elaborates on the categories and part of the results of the assessment.

Sediment management strategy
Porto Amboim

Performance indicator	LOW - 1	MEDIUM - 2	HIGH - 3	Importance (1-3)	Strategy 1a	Strategy 1b	Strategy 2	Strategy 3a	Strategy 3b	Strategy 4a	Strategy 4b
REDUCE					3	3	3	2	2	2	1
Reduction of sedimentation in the port after the measure	Little reduction of sedimentation	Reduction of sedimentation in the port	Large reduction of port siltation	1	3	3	3	2	2	2	1
FINANCIAL					6	4	3	5	3	5	2
NPV; cost indication CAPEX [$]; The cost of **the investment** compaired to the initial cost	High investment cost to start the strategy	Medium investment cost to start the strategy	Low investment cost or no investment cost	1	3	3	1	2	2	2	1
cost indication OPEX [$]; The **operational cost** compaired to the initial operational cost	High operational cost during the operational years	Medium operational cost during the operational years	Low operational cost during the operational years	1	3	1	2	3	1	3	1
OPERATIONAL					4	5	4	4	5	3	4
The measure maintains the **accessibility** in the port.	Still frequent maintenance dredging needed	Some maintenance dredging needed	Maintenance dredging significantly decreased	1	2	2	3	2	2	1	1
The need for **maintenance** and **operational work** of the measure	High operational needs and ongoing maintenance	Medium operational needs	No operational needs and ongoing maintenance	1	2	3	1	2	3	2	3
RESOURCES					5	5	2	4	4	4	4
emmisions [tCO2]; emmisions [tNOx]; The emitted **CO2 and NOx** during the operations of 20 years lifetime	High emissions	Medium emissions	Low emissions	1	2	2	1	2	2	2	2
The amount of **resources needed** to constructed the measure	High amount of resources needed	Medium amount of resources needed	Little resources needed	1	3	3	1	2	2	2	2
ENVIRONMENTAL					4	4	4	2	2	4	4
The **change** in the ecosystem due to the meassure	Negative changes to the ecosystem, endangering the system	Some change to the ecosystem negative and positive	Positive contribution to the ecosystem	1	2	2	2	1	1	2	2
The **turbidity** levels during the construction and operation	Much higher turbidity levels than normal	Some turbidty increase in the area	No turbidty increase, turbidity decrease	1	2	2	2	1	1	2	2
COMMUNITY (LOW - 1 / MEDIUM - 3 / HIGH - 3)					7	5	9	7	6	7	6
New **jobs** for the local community	No new jobs created	A few new jobs create depending on the contract	Several new jobs created and more to come	1	2	1	3	3	2	3	2
Positive **impact** on the local community	Operating port again some positive impact	The port is operating again and other positive impact community	The stratgy has positive impact on the community	1	3	1	3	2	1	2	1
Sediment management strategy avoids **erosion**	The measure ignores the occuring erosion	The measure takes erosion problems into account	The measure actively manages erosion problems in the area	1	2	3	3	2	3	2	3

	Strategy 1a	Strategy 1b	Strategy 2	Strategy 3a	Strategy 3b	Strategy 4a	Strategy 4b
	Sediment trap	Sediment trap	Sediment bypass sytem	Blocking structure	Blocking structure	Natrual sediment bypass	Natrual sediment bypass
	own equipment	contractor		own equipment	contractor	own equipment	contractor
TOTAL	29	26	25	24	22	25	21
REDUCE	3	3	3	2	2	2	1
Reduction	Sedimentation in the sediment trap and with bar dragged into the trap	Sedimententation in the trap, large decrease in the port	All sediment in the port is dredged away with the portable bypass system	Sediment trapped in the buffers before the port, still some siltation due to the not trapped sediment	Sediment trapped in the buffers before the port, still some siltation due to the not trapped sediment	Part of the sediment bypassed due to the extend breakwater, still some port siltation	Part of the sediment bypassed due to the extend breakwater, still some port siltation
FINANCIAL	6	4	3	5	3	5	2
NPV	$ 18.034.135,85	$ 39.059.042,27	$ 31.287.612,63	$ 21.591.828,16	$ 43.001.349,36	$ 19.681.198,79	$ 47.583.118,00
CAPEX	$ 9.250.000,00	$ 9.800.000,00	$ 17.250.000,00	$ 12.950.000,00	$ 13.900.000,00	$ 12.145.000,00	$ 20.125.000,00
Investment	Investment in own dredging equipment and some investment cost by dredging the initial trap	Cost for dredging initial trap and spit removal	High investment cost for the system; suction head, pumping station and pipeline	Cost for the construction of the groynes and investment in own dredging equipment	Cost for the construction of the groynes and spit removal	Cost for the extention and construction of the breakwater and investment in own equipment	Cost for extention and construction of the breakwater
OPEX	$ 467.500,00	$ 1.900.000,00	$ 1.125.000,00	$ 467.500,00	$ 1.900.000,00	$ 377.500,00	$ 1.810.000,00
Operational cost	Operational and maintenance cost of the dredging equipment	Cost for the dredging campaigns of the contractor	Operational and maintenance cost of the sediment bypass system	Operational and maintenance cost of the dredging equipment	Cost for the dredging campaings of the contractor and monitoring the structures	Operational and maintenance cost of the dredging equipment	Cost for the dredging campaings of the contractor and monitoring the structures
OPERATIONAL	4	5	4	4	5	3	4
Accessibility	Maintenance to ensure trap efficiency with drag barring	The need for maintenance dredging depends on the trapping efficiency	Maintenance dredging depends on the efficiency of the SBS expeted to be less	Maintenance dredging needed when buffer area is not able to store sediment	Maintenance of the buffer zone is needed to store enough sediment	Maintenance dredging needed to maintain the port entrance and remove accumalted sand in the port	Maintenance dredging needed to maintain the port entrance and remove accumalted sand in the port
Maintenance and operational work	Operational demands of the DOP and own responsibility to maintain the trap	Maintenance dredging of the trap carried out by a contractor no own maintenance	High operational demans of the system and maintenance needs	The dredging operations with the DOP are own responsibility and maintenance needs	No operation demands as maintenance dredging is carried out by a contract	The dredging operations with the DOP are own responsibility and maintenance needs	No operation demands as maintenance dredging is carried out by a contract
RESOURCES	5	5	2	4	4	4	4
emmisions [tCO2]	11395,93	13295,25	37986,43	11395,93	13295,25	9876,47	11775,79
emmisions [tNOx]	79,59	92,86	265,30	79,59	92,86	68,98	82,24
CO2 and NOx	Emissions during dredging operations of the DOP	Emissions during mob/demob of the dredger and operations every two years	Emissions of the system in operation during the year	Emissions during dredging operations of the DOP	Emissions during mob/demob of the dredger and operations every two years	Emissions during dredging operations of the DOP	Emissions during mob/demob of the dredger and operations every two years
Resources needed	Only dredging equipment needed	Only dredging equipment needed	Installation of a large sediment bypass system and small blocking structure	Construction of blocking structure requires recourses and materials	Construction of blocking structure requires recourses and materials	Construction of the breakwater requires recourses and materials	Construction of the breakwater requires recourses and materials
ENVIRONMENTAL	4	4	4	2	2	4	4
Change	Change in ecosystem durning the construction of the trap but no further disturbance	Change in ecosystem durning the construction of the trap but no further disturbance	System restores the sediment balance in the system, some disturbance near the inlet	Disturbance on the beach were the groynes are constructed	Disturbance on the beach were the groynes are constructed	Distrubance during construction but new ecosystem near the breakwater	Distrubance during construction but new ecosystem near the breakwater
Turbidity	During dredging increase in turbidity in the port	During dredging increase in turbidity in the port	During suction of the system some turbidity in the port	Disturbance in the nearshore beach area during construction and maintenance dredging	Disturbance in the nearshore beach area during construction and maintenance dredging	Turbidity during construction and maintenance dredging in the port	Turbidity during construction and maintenance dredging in the port
COMMUNITY	7	5	9	7	6	7	6
Jobs	Operation and maintenance of the dredging equipment creates jobs	No new jobs created	Construction, operation and maintenance of the system creates new jobs	Construction, operation and maintenance of the system creates new jobs	Construction of the groynes will create new jobs	Construction, operation and maintenance of the system creates new jobs	Construction of the groynes will create new jobs
Impact	Actively management, operationg port and jobs have a postive impact on the community	Operating port has a postivitive impact on the community	Innovative system, operating port and jobs have a positive impact on the community	Operating port and new jobs have a postivitive impact on the community	Operating port has a postivitive impact on the community	Operating port and new jobs have a postivitive impact on the community	Operating port has a postivitive impact on the community
Erosion	Depositing of dredged material near the eroded areas	Depositing of dredged material near the eroded areas of Porto Amboim	Actively pumping of material around the port back into the system	Depositing of dredged material near the eroded areas	Depositing of dredged material near the eroded areas of Porto Amboim	Stimulating sediment bypassing back into the system and deposit dredged material near eroded areas	Stimulating sediment bypassing back into the system and deposit dredged material near eroded areas

Figure 4.25: Assessment of the strategies with performance indicators

For the assessment of the potential strategies several performance indicators are selected. The following twelve performance indicators will be used in the assessment to find the best fit sediment management strategy. The selection of indicators is based on the case study, sediment management objectives, and the area-specific characteristics. The cost [$\$USD$] and emission [kg, tonnes] indicators will be quantified to better assess the potential strategies. The other indicators will be assessed qualitatively.

1. *Reduction of sedimentation*: indicates the amount of reduction of sedimentation in the port obtained by the measure.
2. *Investment cost*: indicates the investment cost compared to the initial cost in USD.
3. *Operational cost*: compares the operational cost of the measure to the initial operational cost in USD.
4. *Maintain accessibility*: indicates the ability of the measure to ensure the accessibility in the port and if dredging is still needed.
5. *Operational work and maintenance*: indicates the work and needed maintenance on the measure when in operation.
6. *Emissions*: indicates the CO_2 and NOx emissions of the measure in kg or tonnes.
7. *Resources efficiency*: indicates the number of resources needed to apply the measure.
8. *Ecosystem change*: compares the changes in the ecosystem due to the measure to the initial ecosystem.
9. *Turbidity*: indicates the levels of turbidity caused by the measure during construction and operation.
10. *Jobs*: indicates the increase in jobs due to the new strategy.
11. *Impact on the community*: indicates the positive impact on the community due to the measure.
12. *Management of erosion*: indicates how the measure takes the occurring erosion problems in the area into account.

Reduce
This performance indicator indicates the amount for reduction created by the measure. Reducing siltation makes it possible to dredge less frequent in the port. An estimation of the reduction is made based on case study examples and the strategy design. This reduction rate determines the additional need for maintenance dredging, the amount, and frequency. It is interesting to compare the strategies on this indicator, because a reduction can reduce the strategy's cost and environmental impact.

Financial
Costs are always an important factor influencing the choice for the final strategy. A good understanding of the several aspects influencing the total cost is therefore important. In this assessment the financial performance indicators investment cost, CAPEX, and operational cost, OPEX are quantified. In the table below, a summary of the costs can be found and a more detailed description of the cost estimation can be found in appendix C. In the assessment, the Net Present Value (NPV) (4.1) of the strategy is also taken into account and showed in Figure 4.26 for the life time of 20 years. The NVP gives inside in the investment needed for the strategy over 20 years.

	strategy 1a	strategy 1b	strategy 2	strategy 3a	strategy 3b	strategy 4a	strategy 4b
CAPEX	$9,250,000	$9,800,000	$17,250,000	$12,950,000	$13,900,000	$12,145,000	$20,125,000
OPEX	$467,500	$1,900,000	$1,125,000	$692,500	$1,900,000	$377,500	$1,810,000
NVP	$18,034,136	$39,059,042	$31,287,613	$24,433,305	$43,001,350	$19,681,199	$47,583,118

Table 4.7: Cost overview sediment management strategies

In the decision-making tool, the input for the cost assessment can be varied according to the case-specific conditions if quantification is required. It is also possible to indicate which aspect has the most influence on the total cost. Important aspects influencing the cost for this case study are the large volume of the spit, the dredging cost per m^3, the return rate, the initial investment for the strategy, and the mobilisation and demobilisation cost of the dredging contractor.

$$NPV = \sum_{i=1}^{n} \frac{values_i}{(1 + rate)^i} \tag{4.1}$$

NPV	Net Present Value
i	years
$values$	yearly cost CAPEX and OPEX
$rate$	yearly discount rate 4%

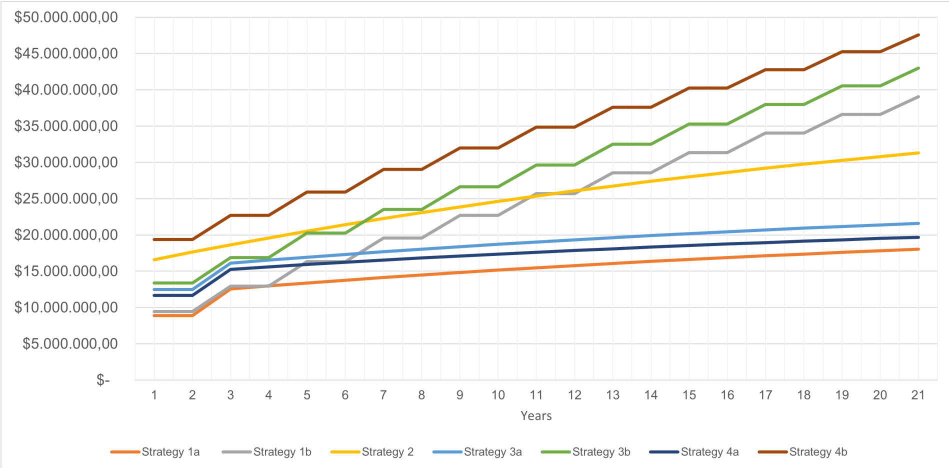


Figure 4.26: NVP proposed strategies over 20 years with a yearly discount rate of 4%

Operational
This category evaluates the operational aspects of the strategies with performance indicators *4.maintain accessibility* and *5.operational work and maintenance*. This is important for the overall port operations. High operational demands can be interesting for the community, because it creates jobs, but it can also be difficult, because it gives a high responsibility for the success of the strategy. The needed maintenance and operational work and the influence on the accessibility are assessed.

Resources
Several resources are needed to realize the various strategies. This category assesses the impact on the resources of each strategy. Two indicators are used for this; *6.emissions* and *7.resources efficiency*. In this assessment the emissions are quantified. An overview of the emissions of the strategies can be found in Table 4.8 below given in tonnes CO_2 and NOx.

	strategy 1a	strategy 1b	strategy 2	strategy 3a	strategy 3b	strategy 4a	strategy 4b
tCO_2	11,395.93	13,295.25	30,386.15	11,395.93	13,295.25	9,876.47	11,775.79
$tNOx$	79.59	92.86	212.24	79.59	92.86	68.98	82.24

Table 4.8: Emission overview sediment management strategies

The input for the emission calculations can also be varied in the tool. The dredging equipment and other equipment used in the strategy determine the required input. The important aspects determining the total emission are the emission factor, the engine type, the working hours, and the equipment used (see 4.2). The input gives a rough estimate of the emission of the strategy. A more detailed understanding of the equipment's processes and workability is needed to find the exact values of the emissions. This detailed assessment can also give insights into the aspects with the most influence on the emissions. Identification of these aspects allows seeing where the reduction of emissions is possible.

$$E_j = \sum (P_i * LF_i) * A * EF_j \tag{4.2}$$

E	emissions [g]
P_i	power [kW]
i	engine type or pumps
LF_i	engine load factor [-]
	percentage of vessel's total power
A	activity working hours [h]
EF	emission factor [g/kWh]
EF_{CO_2}	680 [g/kWh]
EF_{NOx}	4.75 [g/kWh]

Environmental
The focus on the environment grows more every year. In this category, several environmental aspects are assessed to indicate the impact on the environment of the measure. As maintenance dredging in the port often influences the ecosystem (performance indicator 8) and the turbidity (performance indicator 9) in the port area, the strategies are assessed on these aspects. This category indicates the strategy with the lowest and highest impact on the environment.

Community
This category assesses the impact on the community of the strategy. A positive impact on the community is an interesting factor to compare the strategies on. This impact can show the added value of a strategy even if its performance less in other categories. In this assessment the performance indicators *10.jobs*, *11.impact on the community*, and *12.management of erosion* are assessed to identify this impact.

4.5. Application of the strategy

This section describes the last stap of the approach, *application of the strategy*. In the decision-making tool, the strategies are assessed in detail, and the scores per category are assessed in a stability and sensitivity analysis. In this analysis, the importance of the categories is varied with a weight factor. The following results are obtained from the assessment and the stability and sensitivity analysis.

Sensitivity analysis

		Weight	Strategy 1a	Strategy 1b	Strategy 2	Strategy 3a	Strategy 3b	Strategy 4a	Strategy 4b
	Category		Sediment trap	Sediment trap	Sediment bypass sytem	Blocking structure	Blocking structure	Natrual sediment bypass	Natrual sediment bypass
			29,00	26,00	25,00	24,00	22,00	25,00	25,00
1	Reduce	17%	3,00	3,00	3,00	2,00	2,00	2,00	2,00
1	Financial	17%	6,00	4,00	3,00	5,00	3,00	5,00	5,00
1	Operational	17%	4,00	5,00	4,00	4,00	5,00	3,00	4,00
1	Resources	17%	5,00	5,00	2,00	4,00	4,00	4,00	4,00
1	Environmental	17%	4,00	4,00	4,00	2,00	2,00	4,00	4,00
1	Community	17%	7,00	5,00	9,00	7,00	6,00	7,00	6,00
0									
0									
	Total score, weigthened	**100%**	4,83	4,33	4,17	4,00	3,67	4,17	4,17
		Result Stability	1751	416	575	0	4	0	0
			63,8%	15,1%	20,9%	0,0%	0,1%	0,0%	0,0%
		Result Sensitivity	28633	4267	6436	0	0	0	0
			72,8%	10,8%	16,4%	0,0%	0,0%	0,0%	0,0%

Figure 4.27: Results assessment and sensitivity analysis

Furthermore, the total scores are assessed on effectiveness of the prevention measure resulting in weighted total scores. The results of this assessment are given in Table 4.9 below. This results indicate strategy 1a, *sediment trap with own equipment* as the best score but also show the potential of strategy 2, *sediment bypass system*.

	strategy 1a	strategy 1b	strategy 2	strategy 3a	strategy 3b	strategy 4a	strategy 4b
score	29	26	25	24	22	25	21
weight	80%	80%	90%	90%	90%	70%	70%
weighted score	23.2	20.8	22.5	21.6	19.8	17.5	14.7

Table 4.9: Total scores with the effectiveness included

From the results can be concluded that strategy 1a, *sediment trap with own equipment* is the best fit strategy for Porto Amboim for sustainable sediment management. The second-best strategy is strategy 2, *sediment bypass system*. These strategies (Figure 4.28) are meeting the sediment management objectives the best and have the potential to manage the sediment in the Porto Amboim area.

Figure 4.28: The proposed strategies after the assessment with the decision-making tool

In this chapter a case study is worked out in detail to identify the various aspects needed to obtain a sediment management strategy. This detail description of the case and extensive case study allowed to develop the decision-making approach and tool further as part of this research. The following section reflects upon the results of the case study.

4.6. Reflection on results of case study: Porto Amboim

The decision-making approach has been used to find a sediment management strategy for Porto Amboim. In the port of Porto Amboim sedimentation problems make several port operations difficult. With the decision-making approach and the assessment of the potential strategies, a sediment management strategy is found and proposed for Porto Amboim for the coming 20 years. This section reflects on the results of the case study and describes the uncertainties in the process.

Available information

The information available on a case study varies per study and port. Suitable information sources can vary and come from the port itself, a consultancy company, research institutes or available open source data. The level of detail needed of the data depends on the goal of the assessment. A small amount of data can be sufficient if a quick analysis is required for potential sediment management strategies. With more available data, a more detailed assessment of the potential sediment management strategies is possible. A trade-off needs to be made between the desired level of detail to apply in the assessment and the available information. If a certain level of detail is required, it is important to have detailed information on all aspects of the port. Otherwise it is not possible to compare all the potential strategies on the same level.

For this case study information from an old Arcadis project and open source data has been used. Open source data from *Google Earth Pro*, satellite imaging, on the bathymetry, and from the website of the port authority is accessed. With the availability of these sources it has been possible to analyse the coastal system and sediment balance over the past ten years. The description of the coastal system with some simplifications and approximations is used to choose the potential prevention methods and to assess different sediment management strategies. The level of detail of the system analysis was adequate to obtain potential strategies and to use the decision-making tool to find the most suitable strategy. From this case study it can be concluded that with only using the open source data available an adequate assessment can be applied to optimize the sediment management strategy for a port. The information minimally needed to perform an assessment, is a good description and understanding of the coastal system and the sediment balance in the port area.

The potential strategies

Due to the simplification of the coastal system, uncertainty in the assessment is more likely to occur. The uncertainty in the coastal system analysis has the most significant impact on the working principles of the prevention measures. The (un)certainty of the working principles determines the efficiency of the prevention measure, which makes it important to consider. However, it is still possible to make a good assessment of the potential strategies with a simplified coastal system analysis. The potential strategies are assessed on several aspects that are important for the decision-making process. The (un)certainty in the effectiveness of the working principles is separately assessed in the assessment by means of a weighted total score. With this weighted score the strategies can be compared with decreased uncertainty.

In the case study the strategies are assessed in combination with dredging with own equipment and dredging by a contractor. This distinction between two maintenance dredging methods makes it possible to assess the strategy on different execution methods. For dredging with own equipment the DOP dredger is considered in this case study. However, there are other dredgers available to be purchased by the port authority and used for the maintenance dredging. The DOP dredger is a good example of a dredger meeting the maintenance requirements in this case. Additionally, it can be interesting to consider other dredging equipment or dredging contracts as well, for example the purchase of dredging equipment in cooperation with other ports in the area to divide the cost and use the equipment more efficiently.

The proposed strategy

The assessment of the case study resulted in a sediment management strategy for Porto Ambiom, *sediment trap with own equipment*. This strategy manages the sediment in the port area, nourishes the eroded beaches further up north and creates jobs for the community in the Porto Amboim area. The main working principle of the strategy is to create a buffer zone to store sediment between two dredging campaigns, managing the sediment. An aspect that needs to be considered is the increased responsibility for the port authority to carry out the operations and maintenance. In a next phase, it is recommend to involve also other stakeholders to investigate if this increased (local) responsibility can be established. An additional aspect to consider is the development of a more detailed design. Further research is recommended to find the most efficient location, depth and configuration of the sediment trap.

From the sensitivity analysis and the effectiveness assessment can be obtained that the second-best performing strategy is a *sediment bypass system*. This strategy is an innovative management approach for Porto Amboim, creating opportunities for employment and adaptive sediment management. Aspects to consider in this approach are the great responsibility for the operators of the system to obtain an efficient strategy. Intensive operational work and maintenance is needed to let the system work efficient. Also, the investment costs of the system are high, making it difficult to create a business case for this strategy. However, this strategy has great potential to manage the sediment in the area and has a positive influence on the community, as it creates jobs and responsibility. The system adaptive sediment management can be applied to counteract the sedimentation problems and nourish the eroded beaches. In addition the use of renewable energy resource to operate the system increases the potential and efficiency of this strategy, contributing to more sustainable sediment management in this area.

Despite the described uncertainties, two suitable sediment management strategies have been obtained for this case study with the available information. The developed decision-making approach supports the process to obtain and assess several potential strategies. In the next phase, a more detailed design and analysis of the coastal system will lead to the final sediment management strategy for Porto Amboim.

4.7. Summary

Porto Amboim is a port in Angola and in the need of a sufficient sediment management strategy. Currently no strategy is applied and large volumes of sand accumulate in the port area, hindering the port operations. The sedimentation rate in the port at the lee side of the port breakwater is 130.000 to $180.000 m^3/yr$. This accumulation and the sediment transport is driven by a longshore sediment transport rate of 250.000 to $300.000 m^3/yr$ and southwestern offshore waves. Furthermore, erosion further up north occurs due to a dis-balance in the system.

In the case study the decision-making approach is applied to find a suitable sediment management strategy for Porto Amboim. With the analysis of the current state of the system sediment management objectives are defined (*step 1*). In *step 2* four prevention methods are selected and worked out in more detail. In *step 3* the potential strategies are assessed with twelve performance indicators. This assessment resulted in two suitable strategies for the case Porto Amboim shown in *step 4*.

In the reflection the available information, potential strategies and proposed strategies are discussed. From this case study it can be concluded that when only using open source data still an adequate assessment can be applied to optimize the sediment management strategy. The minimal needed information to perform an assessment is a proper description and understanding of the coastal system and the sediment balance. The working principles of the prevention measures creates the biggest uncertainty in the assessment. The additional assessment of the effectiveness reduces this uncertainty. In the sediment management strategies, the additional dredging is limited to dredging with a DOP and dredging with a contractor, however there are more interesting ways of dredging to identify and consider as potential options for the strategies.

With the decision-making approach a sediment management strategy is obtained for Porto Amboim. The most suitable strategy resulting from the tool considers a sediment trap and dredging with own equipment. A few aspects are not considered in the approach and still need to be considered in the next phase of the development of the sediment management strategy. Closer involvement of the stakeholders is beneficial to assess the practical applicability of the strategy and responsibilities. An additional aspect to consider is the development of a more detailed design. Further research is recommended to find the most efficient location, depth, and configuration of the sediment trap. Furthermore, the second-best strategy, the sediment bypass system, also has great potential to optimize the sediment management for this project location.

The following chapter assesses the decision-making approach further with a second case study and expert session. With this validation the generic use of the approach will be identified.

5

Validation and generic use

This chapter describes the validation of the developed decision-making approach and tool. A validation is performed with a case study of the Tweed River Entrance and an expert session at Arcadis. The validation results are use to analyse the potential of generic used of the approach and the tool.

5.1. Validation with a case study

To validate the workability of the decision-making approach and tool, a sediment management strategy is analysed for the Tweed River Entrance. This project focuses not on a port but on a river entrance. This river is important for the area because of its high economic value, therefore sediment management is needed at this location. In the Tweed River Entrance and in the surrounding area, sediment is managed with a sediment bypass system. The validation gives insight into the alternative strategies and the assessment indicates the most potential strategy for this case study. The assessment indicates if the optimal sediment management strategy is currently applied in this case study. The four steps of the decision-making approach; *1 - Sediment management objectives*, *2 - Fit to case*, *3 - Assessment of strategies*, and *4 - Meeting the objectives* are considered for the Tweed River Entrance.

Figure 5.1: Tweed river entrance along the coast and the sediment bypass system (Tweed Sand Bypassing, 2020)

5.1.1. Tweed River Entrance

The Tweed River is located in New South Wales and Queensland (Australia) near the southern Gold Coast beaches. The river and the beaches are currently managed with a sediment bypass system installed near the river entrance in combination with intermittent maintenance dredging. Figure 5.1 shows a picture of the river entrance and the system installed at the upstream side of the entrance.

1 - Sediment management objectives
Current state of the system
The sediment bypass system was constructed in 2001 to counteract the sediment problems near the river entrance of the Tweed River. The major sediment management problems before the sediment bypass system are indicated in Figure 5.2. The occurring problems were; sedimentation behind the training wall, sedimentation on the shoal in front of the river entrance, and erosion at the North Kirra beach. Sedimentation in and near the river is not desired as it obstructs the navigation channel. A navigable channel is required for the sea going vessels and fishermen from the Tweed River and the surrounding ports. The second reason why the sediment bypass system is constructed is to nourish the eroding southern Gold Coast beaches down-drift of the Tweed River Entrance. The beaches are very important in this area because of the high economic value for citizens, entrepreneurs, tourists, beach house owners, and surfers. The optimized sediment management strategy should take these objectives into account.

Figure 5.2: The Tweed River Entrance before the construction of the sediment bypass system. The sedimentation behind the training wall and at the river entrance and the erosion at North Kirra are indicated. (Tweed Sand Bypassing, 2020)

The transported sand along the Australian west coast originates from large sand deposits just off-shore of the Clarence River near Yamba. From these deposits the sand moves in northward direction. The sediment transport along the Tweed and Gold Coast beaches is therefore predominantly northward directed. South-eastern waves approaching the coast transport the sand along the coast and beaches. The waves have an average significant wave height of $1.23m$. The yearly sediment transport rate is 500,000 m^3/yr. The refracting waves around the Snapper Rocks headland transport the sand further up north along the Gold Coast beaches. The Tweed River Entrance interrupts this natural longshore drift with the training walls guiding the river. This interruption results in a need for sediment management of 500,000 m^3/yr. The sediment management strategy should take this interruption into account and consider a sediment management method stimulating the natural longshore drift.

Sediment management objectives
In the assessment alternative sediment management strategies will be assessed together with the current sediment bypass system strategy. The alternative sediment management strategies should consider the following sediment management objectives. These objectives will be assessed with several performance indicators.

- The strategy maintains a navigable depth in the Tweed River.
- The strategy nourishes the Gold Coast beaches downstream.
- The strategy stimulates the natural longshore drift.
- The strategy creates a storm buffer along the beaches.
- The strategy ensures excellent surfing conditions for the surfers.
- The strategy minimizes the environmental impact.

Figure 5.3: Overview of the Tweed River area and the longshore transport direction.

2 - Fit to case
In this step all the prevention methods for sediment management are considered for this case study. This results in two interesting prevention methods to assess as alternative strategies; *Guiding structure* and *natural sediment bypass*.

	Suitable	Reasoning
Sediment trap	no	high longshore transport rate not possible to trap all the sediment
Sediment bypass system	*yes*	*current strategy*
Habitat creation	no	no nourishment of the eroding beaches
Blocking structure	no	the training wall already acts like a blocking structure
Blocking screen	no	would not stop the shoal formation
Guiding structure	yes	an extension of the training walls can be interesting
Natural sediment bypass	yes	possible to stimulate at river entrance
Resuspension of sediment	no	no fine sediment and high current velocities
Fluid mud	no	no fine sediment in the area
Bed levelling	no	no specific basin area interesting to use this method

Table 5.1: Pre-assessment of prevention methods suitable for sediment management in Porto Amboim

Current strategy
The current system constructed south of the Tweed River entrance consists of eleven jet pumps installed on a 450 m long jetty. The maximum pumping capacity of the jetty is 500 m^3 per hour, this rate is obtained when four pumps operate simultaneously (Cox and Howe, 2012). The annual transport rate varies from 250,000 to 1,000,000 m^3/yr (Boswood et al., 2005). The dredged slurry is pumped via a buried pipeline under the Tweed River to outlets at Snapper Rocks East, Snapper Rocks West, Kirra Point, and Duranbah Beach (see Figure 5.3). Adaptive sediment management can be applied along the beaches with the multiple outlet locations. The initial project investment cost were $23.3M Australian dollar. The project annual operational costs varied in the past ten years from $3.7M to $6.8M Australian dollar ($2.9M to $5.3M). These costs are equally divided between the NSW and Queensland governments Tweed Sand Bypassing (2020). The strategy started operating in 2001 and now resulted

in a navigable Tweed River, wider beaches, better amenity, a demonstrated storm buffer, and surfing benefits (Boswood et al., 2005) in the Tweed River and Gold Coast area.

Alternative 1 - Guiding structure

At this location a guiding structure is already in place, the training walls at the river entrance. This strategy proposes an extension of the training walls to obtain a navigable port entrance. Currently, a shoal is formed in front of the river entrance. Sediment settles on the shallower area in front of the entrance forming this shoal. Figure 5.4 indicates the shallow zone (darker colour), this zone is located in front of the river entrance. An extension of the two training walls of $200m$ through this shallow zone can decrease the sediment settlement on the shoal as the sediment is guided away from the shallower zone, see Figure 5.5. The sediment is transported further up north to continue in the longshore drift.

To obtain this strategy, in the first phase, the extension of the training walls needs to be completed. After the construction, monitoring of the sediment transport patterns and sedimentation rates will give more insight into the additional maintenance dredging needed. For the assessment a bypassing rate of 20% per year is assumed. Intermittent maintenance dredging is required as still sand will accumulate near the entrance and at the upstream side of the training wall. A dredging campaign every two years is assessed in this strategy.

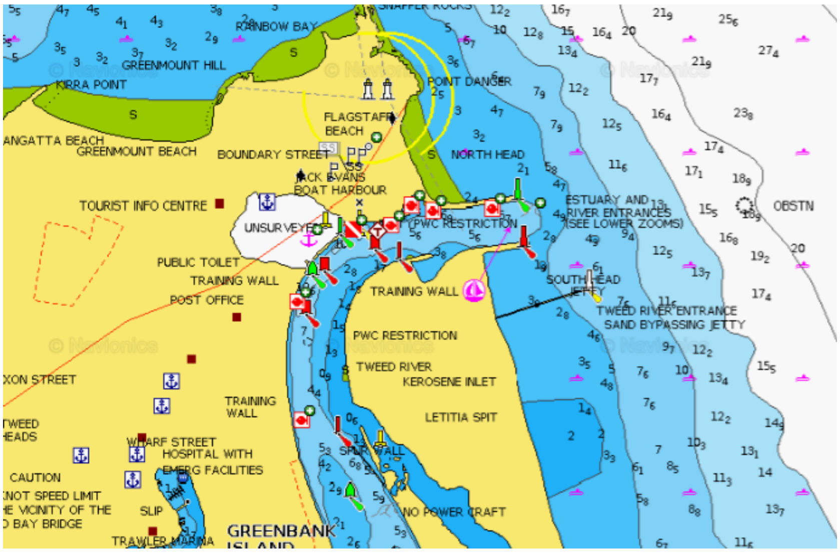


Figure 5.4: Bathymetry Tweed River Entrance (Navionics ChartViewer, 2021)

Alternative 2 - Natural sediment bypass

The working principle of this strategy is to stimulate the sediment transport flow to enhance natural sediment bypassing. The flow is stimulated with a guiding structure around a the river entrance heads. For this case study streamlined breakwaters are proposed at the Tweed River Head as can be obtained in Figure 5.6. The streamlined breakwaters will increase the flow velocity by contraction around the breakwaters and will extend the navigation channel through the shallow zone to create an equal channel depth and natural depth.

To obtain this strategy, in the first phase, the streamlined breakwaters of $150m$ and $350m$ need to be constructed. After the construction, monitoring of the sediment transport patterns and sedimentation rates will give more insight into the additional maintenance dredging needed. For the assessment a bypassing rate of 25% per year is assumed. Intermittent maintenance dredging is required every two years as still sand will accumulate near the entrance and at the southern side of the breakwater.

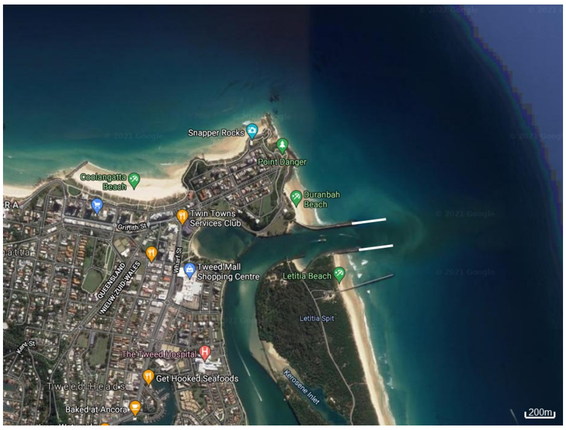


Figure 5.5: Sediment management alternative 1
Guiding structure

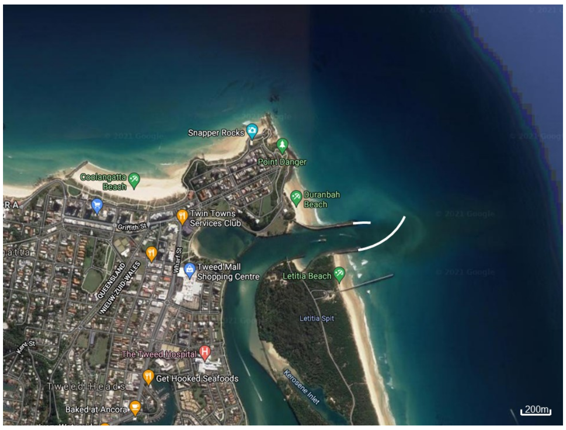


Figure 5.6: Sediment management alternative 2
Natural sediment bypass

Alternative 3 - Maintenance dredging with own equipment
This alternative considers only maintenance dredging to manage the sediment in this area. The purchase of own dredging equipment enables a yearly dredging campaign to manage the sediment near the Tweed River Entrance. The accumulated sediment south of the training wall and in front of the entrance on the shoal needs to be dredged to ensure a navigable depth and nourish the down-drift beaches. The location south of the training wall will function as a buffer zone to store sediment during the year. Not all the sediment will accumulate in this zone, as a part of it will continue with the littoral drift and form a shoal in front of the entrance. It is expected that an amount of 500,000 m^3 needs to be dredged every year. The dredged material will be placed near Duranbah Beach, Snapper Rocks and Kirra Point to maintain sufficient beach conditions.

3 - Assessment of potential strategies
In the assessment the four strategies are assessed with twelve performance indicators, see Figure 5.7. The complete assessment can be found in the attached *Microsoft Excel* file *Decision-making tool - Tweed River Entrance*.

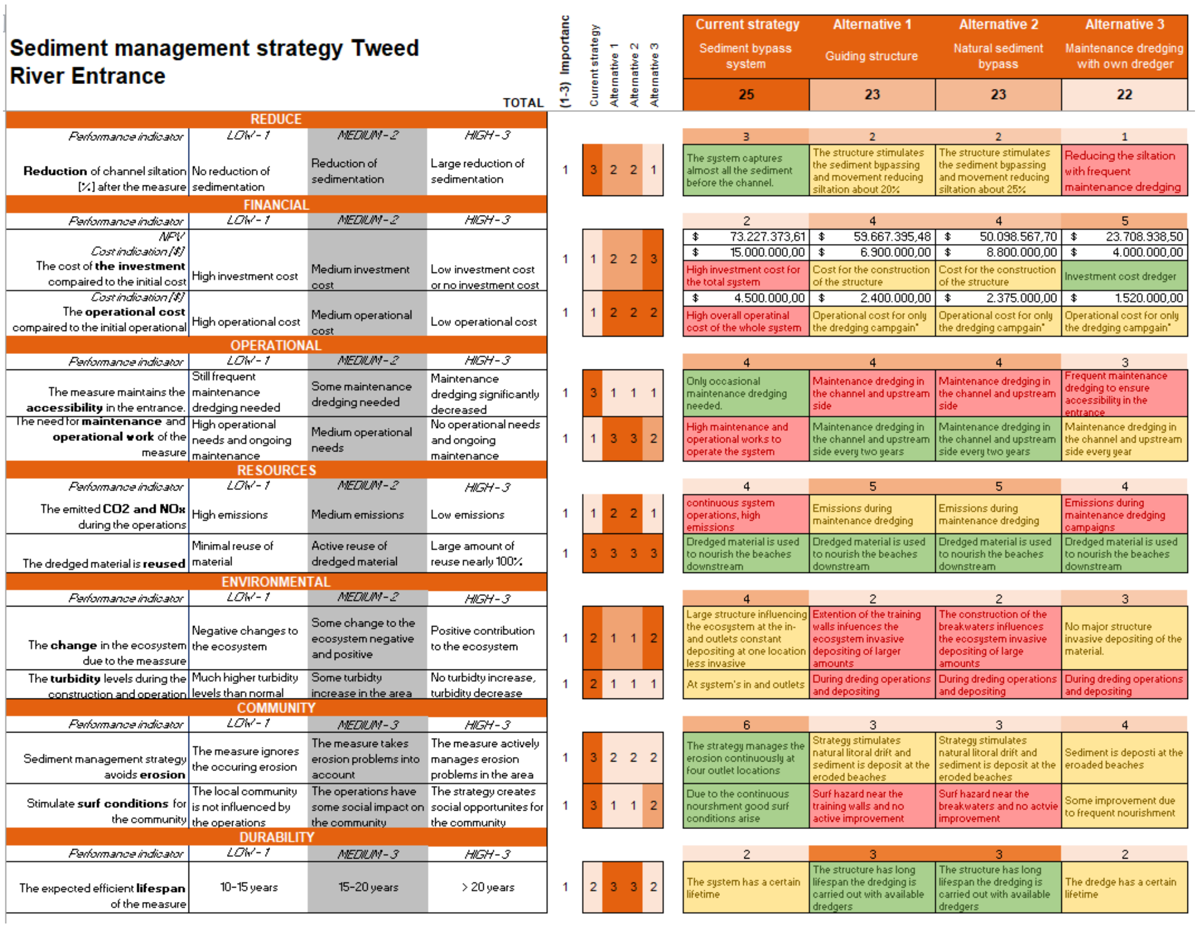
4 - Application of the strategy
The strategy performing best in the assessment is the current strategy, the sediment bypass system. This strategy is meeting the sediment management objectives for the Tweed River Entrance. From the sensitivity analysis, Table 5.2, and the effectiveness assessment, Table 5.3, can be obtained that the second best strategy is maintenance dredging with own equipment.

	current strategy	alternative 1	alternative 2	alternative 3
Results stability	15238	0	0	2168
	87,5%	0,0%	0,0%	12,5%
Results sensitivity	215481	0	0	31032
	87,4%	0,0%	0,0%	12,6%

Table 5.2: Results stability and sensitivity analysis alternative strategies for Tweed River Entrance

	current strategy	alternative 1	alternative 2	alternative 3
score	25	23	23	22
weight	100%	90%	90%	100%
weighted score	25	20.7	20.7	22

Table 5.3: Total scores with the effectiveness included for Tweed River Entrance



Sediment management strategy Tweed River Entrance

Performance indicator	LOW - 1	MEDIUM - 2	HIGH - 3	(1-3) Importanc	Current strategy	Alternative 1	Alternative 2	Alternative 3	Current strategy: Sediment bypass system	Alternative 1: Guiding structure	Alternative 2: Natural sediment bypass	Alternative 3: Maintenance dredging with own dredger
TOTAL									25	23	23	22
REDUCE									3	2	2	1
Reduction of channel siltation [%] after the measure	No reduction of sedimentation	Reduction of sedimentation	Large reduction of sedimentation	1	3	2	2	1	The system captures almost all the sediment before the channel.	The structure stimulates the sediment bypassing and movement reducing siltation about 20%	The structure stimulates the sediment bypassing and movement reducing siltation about 25%	Reducing the siltation with frequent maintenance dredging
FINANCIAL									2	4	4	5
NPV									$ 73.227.373,61	$ 59.667.395,48	$ 50.098.567,70	$ 23.708.938,50
Cost indication [$] The cost of **the investment** compaired to the initial cost	High investment cost	Medium investment cost	Low investment cost or no investment cost	1	1	2	2	3	$ 15.000.000,00 High investment cost for the total system	$ 6.900.000,00 Cost for the construction of the structure	$ 8.800.000,00 Cost for the construction of the structure	$ 4.000.000,00 Investment cost dredger
Cost indication [$] The **operational cost** compaired to the initial operational	High operational cost	Medium operational cost	Low operational cost	1	1	2	2	2	$ 4.500.000,00 High overall operatinal cost of the whole system	$ 2.400.000,00 Operational cost for only the dredging campgain*	$ 2.375.000,00 Operational cost for only the dredging campgain*	$ 1.520.000,00 Operational cost for only the dredging campgain*
OPERATIONAL									4	4	4	3
The measure maintains the **accessibility** in the entrance.	Still frequent maintenance dredging needed	Some maintenance dredging needed	Maintenance dredging significantly decreased	1	3	1	1	1	Only occasional maintenance dredging needed.	Maintenance dredging in the channel and upstream side	Maintenance dredging in the channel and upstream side	Frequent maintenance dredging to ensure accessibility in the entrance
The need for **maintenance** and **operational work** of the measure	High operational needs and ongoing maintenance	Medium operational needs	No operational needs and ongoing maintenance	1	1	3	3	2	High maintenance and operational works to operate the system	Maintenance dredging in the channel and upstream side every two years	Maintenance dredging in the channel and upstream side every two years	Maintenance dredging in the channel and upstream side every year
RESOURCES									4	5	5	4
The emitted **CO2 and NOx** during the operations	High emissions	Medium emissions	Low emissions	1	1	2	2	1	continuous system operations, high emissions	Emissions during maintenance dredging	Emissions during maintenance dredging	Emissions during maintenance dredging campaigns
The dredged material is **reused**	Minimal reuse of material	Active reuse of dredged material	Large amount of reuse nearly 100%	1	3	3	3	3	Dredged material is used to nourish the beaches downstream	Dredged material is used to nourish the beaches downstream	Dredged material is used to nourish the beaches downstream	Dredged material is used to nourish the beaches downstream
ENVIRONMENTAL									4	2	2	3
The **change** in the ecosystem due to the meassure	Negative changes to the ecosystem	Some change to the ecosystem negative and positive	Positive contribution to the ecosystem	1	2	1	1	2	Large structure influencing the ecosystem at the in- and outlets constant depositing at one location less invasive	Extention of the training walls infuences the ecosystem invasive depositing of larger amounts	The construction of the breakwaters influences the ecosystem invasive depositing of large amounts	No major structure invasive depositing of the material.
The **turbidity** levels during the construction and operation	Much higher turbidity levels than normal	Some turbidty increase in the area	No turbidty increase, turbidity decrease	1	2	1	1	1	At system's in and outlets	During dreding operations and depositing	During dreding operations and depositing	During dreding operations and depositing
COMMUNITY (Performance indicator: LOW - 1, MEDIUM - 3, HIGH - 3)									6	3	3	4
Sediment management strategy avoids **erosion**	The measure ignores the occuring erosion	The measure takes erosion problems into account	The measure actively manages erosion problems in the area	1	3	2	2	2	The strategy manages the erosion continuously at four outlet locations	Strategy stimulates natural litoral drift and sediment is deposit at the eroded beaches	Strategy stimulates natural litoral drift and sediment is deposit at the eroded beaches	Sediment is deposti at the eroaded beaches
Stimulate **surf conditions** for the community	The local community is not influenced by the operations	The operations have some social impact on the community	The strategy creates social opportunites for the community	1	3	1	1	2	Due to the continuous nourshment good surf conditions arise	Surf hazard near the training walls and no active improvement	Surf hazard near the breakwaters and no actvie improvement	Some improvement due to frequent nourishment
DURABILITY (Performance indicator: LOW - 1, MEDIUM - 3, HIGH - 3)									2	3	3	2
The expected efficient **lifespan** of the measure	10-15 years	15-20 years	> 20 years	1	2	3	3	2	The system has a certain lifetime	The structure has long lifespan the dredging is carried out with available dredgers	The structure has long lifespan the dredging is carried out with available dredgers	The dredge has a certain lifetime

Figure 5.7: Assessment of potential strategies for Tweed River Entrance

5.1.2. Results and conclusions case study

In this validation the decision-making approach is used to perform a quick assessment to find a sediment management strategy for the Tweed River Entrance. To obtain a good assessment it is required to apply at least one performance indicator per category. For this assessment twelve performance indicators are used to assess the alternative strategies. The results show that it is possible to identify the potential strategies for sediment management on every location if the required information is available. The most important information considered in this case study is listed below:

- River traffic and operations
- The littoral drift and wave direction
- Sediment transport patterns
- The involved stakeholders
- The economic value of the beach
- The current sediment management strategy

The most potential sediment management method for this location is the sediment bypass system. This strategy is currently actively applied in this area. However, the results can be biased as this strategy is already applied in this area for 20 years. Adaptations to the system in these years resulted in beneficial outcomes and show the potential of the system. An example of such a beneficial outcome is the developed surf bar along the Coolangatta Beach, the world famous surfing ”superbank”, a continuous bar created between the control points of Snapper Rocks and Kirra Point groyne (Boswood et al., 2005). The validation with this case study showed the potential for generic use of the decision-making approach and tool. It is an useful approach to apply in the primary design phase of a port sediment management strategy. With the tool two or three suitable sediment management strategies can be identified for a port project. The tool is also applicable to compare potential strategies in more detailed design stages of the port.

5.2. Validation with expert session

To validate the usability and workability of the decision-making approach and tool a validation session with experts is held. Several experts from Arcadis with experience in port related consultancy projects participate in the expert session.

5.2.1. The expert session

The session was held via *Microsoft Teams* and used to gain insight into the decision-making tool's usability. During this session, the following topics and parts are addressed and discussed:

- Introduction of the research
- Explanation decision-making approach and tool
- Introduction of the case study
- Application approach and tool on the case study
- Evaluation of the session

The case study considered a port in Costa Rica. This case is selected because of the available information, the case is an old project of Arcadis, and the relatively simple to understand coastal system. During the validation session, the experts applied the approach and the tool on the case study to find a sediment management strategy for this port. In an hour-long session, the experts had time to select potential prevention methods and assess the selected methods with performance indicators.

5.2.2. Results and conclusions expert session

The application of the approach and tool by the expert resulted in several comments and additional improvements to primarily the tool. In a short time, it was possible to select several potential sediment management methods and perform an assessment to identify a preliminary suitable prevention method for the case.

The level of detail of the assessment varied for each participating expert. The main reason for this was the experience level and prior knowledge of sediment management methods of the expert. Another reason was the understanding of the workability of the tool. For a part of the expert group, the workability was not clear from the beginning, especially the required input. After several questions and more explanation, the workability became clear. These two reasons can also be obtained from the evaluation of the session. The tool is improved with an explanation sheet and more written explanation is added in the tool to improve the workability.

The main conclusion of the expert session indicated a useful and structured approach to consider and compare several potential prevention methods. Also, the potential of the tool to grow with projects and further development was identified. However, the workability of the tool was not directly clear and could be improved to increase user-friendliness.

5.3. Generic use

The application of the decision-making approach and tool on the Tweed River Entrance case study and in the expert session showed its potential to be used in any case study in need of sediment management. The objective of this research is to develop a decision-making approach and tool to optimize sediment management in the port. The decision-making approach considers all the aspects involved in a sediment management strategy and the decision-making tool contributes to a better assessment of the potential sediment management strategies. This approach and tool are suitable to be generic applied to any case study around the world in need of optimal sediment management.

A quick assessment is possible if a certain level of information on the case study is available and a level of understanding of the approach and the supporting tool is obtained. The minimal data needed for an assessment is:

- Port operations
- The littoral drift and wave direction
- Sediment transport patterns
- The involved stakeholders
- The environmental conditions
- The current sediment management strategy

Understanding of the response of the coastal system and working principles of the prevention measures is needed to obtain a preliminary design of the potential strategies. A good assessment can be applied if performance indicators are used from every category. This also requires a certain level of information and understanding of the objectives. The results of the assessment depend on the stage and detail of the preliminary design. Considering that the tool will be applied for port projects, where a detailed coastal analysis is required, the availability of information will not be a limiting factor. This makes the tool interesting for generic use in several stages of the port design.

This chapter validates the tool with a second case study of Tweed River Entrance and an expert session. From this chapter can be concluded that the developed approach is suitable to find and assess sediment management strategies for these two case studies if minimal data is available. It is possible to compare different prevention methods with selected performance indicators and assess them further with the decision-making tool. In the following chapter, the generic use of the decision-making approach and tool is further discussed, together with the limitations of the research.

6 Discussion

The previous chapter reflected on the case study results and it showed some limitations. The validation of the approach and tool showed the generic applicability of the tool. This chapter discusses the significance of sustainable sediment management. Furthermore, the general applicability, limitations and significance of the decision-making approach and tool will be discussed.

6.1. Sustainable sediment management

In this research the sustainable sediment hierarchy is introduced to obtain sustainable sediment management. The three-step management approach *Prevent and Reduce*, *Reuse and Recycle*, and *Disposal* aims to adopt dredged material as a valuable resource within the coastal system and the port. In this thesis the main focus was on *Prevent and Reduce*, resulting in ten prevention methods of sediment management. These ten methods with different characteristics are suitable to be applied on ports to optimize the sediment management. However, it is also important to consider the *Reuse and Recycle* of dredged material. There are many reuse and recycle possibilities making dredged material a valuable resource, examples are given in Section 2.5 describing this potential. As sediment is being dredged at this moment somewhere around the world, an extra focus on reusing and recycling gives a big opportunity to apply sustainable sediment management already in every port right now.

In conclusion, the use of the sediment management hierarchy considers the value of sediment and dredged material creating opportunities for a more sustainable maintenance strategy of a port.

6.2. The decision-making approach

The developed decision-making approach aims at optimizing the process towards a more sustainable sediment management strategy for a port. In this section the limitations and applicability of the decision-making approach will be discussed.

The developed approach considers all the main aspects of sediment management in the port. However, each port is unique in its characteristics, making it difficult to obtain a generic approach. In this approach well defined sediment management objectives provided the input to select the associated performance indicators. As this step of the approach is mainly based on the stakeholders' input and interest the performance indicators are subjectively determined. To minimize this subjectivity seven standard assessment categories are identified based on literature and expert interviews, see Section 3.2. It is important to use at least one performance indicator in each of these categories. Furthermore, additional performance indicators give insight into case specific characteristics and stakeholders interest and can be added to the categories reducing the subjectivity.

The developed approach is partially based on the *Design of sustainable infrastructure* approach by Laboyrie et al. (2018). The decision-making approach considers most of the aspects from the steps of the literature, but focuses specifically on sediment management in a port. However, there are additional interesting aspects to consider in the decision-making approach, pointed-out by the literature. The *Design of sustainable infrastructure* approach has an additional focus on the ecosystem services, stakeholder involvement, and implementation phase. These aspects stimulate a focus on more sustainable solution also, and include steps towards the implementation phase. Although this depends on the available information, stakeholders and case study objectives, these aspects are important enough to be included in the next design phase of the sediment management strategy.

The adaptive management approach is flexible and able to reduce environmental risk through the analysis of monitoring data and making adaptive decisions during the management process. This research developed an approach to find a long-term sediment management strategy. With the decision making approach a long-term strategy can be obtained taking all the aspects of sediment management into account. However, the sediment management strategy can be improved considering a more adaptive design. Finding an adaptive strategy creates the opportunity to change the strategy over the years. An adaptive strategy creates the possibility to alter the strategy to changes in the system or port optimizing the sediment and reducing the environmental impact. It also gives the opportunity to find a strategy for a longer time period, for several decades. Adaptive strategies can be obtained if various future scenarios are being analysed for the port case study. This requires a good understanding of the coastal system and the future developments in the port. Modelling studies can be used to analyse the coastal system and assess several potential adaptive strategies. Although modelling studies reduce uncertainties, it takes time and effort to find an accurate solution.

In conclusion, there are limitations to the developed decision-making approach. However, despite the limitations it considers all the main aspects to find a sediment management strategy for a port by the use of a structured approach.

6.3. The decision-making tool

This tool consists of four components supporting the decision-making approach; performance indicators, effectiveness, quantification, and sensitivity analysis. These components are being used to assess the potential strategies and find the best sediment management strategy for a port. In this section the limitations and applicability of the tool will be discussed.

In this research the performance indicators are mainly used in relative sense. It can however be interesting to add benchmarks to the indicators and score each strategy's performance with this benchmark. A benchmark can set requirements to a specific indicator. These requirements need to be met by every strategy to be considered and suitable for the port. For example a benchmark for the environmental indicators can assess the performance of the strategies with specific environmental requirements. It is possible to compare the potential strategies in relative sense, however bench marking the indicators can add extra value to the assessment.

In the case study of this research this tool is being used to quantify the cost and emissions of each strategy. This quantification gives a more detailed description of a performance indicator and makes it possible to compare the strategies on a significant level. It is interesting to quantify more performance indicators, because it will give more insight into the differences between and performance of each chosen strategy. Information about the indicator is needed to apply a quantification. If required extra quantification sheets can be added to the tool and applied in the assessment. The tool can grow within the port project. However, this detailed information needs to be available and sufficient enough to make a quantitative assessment. Insufficient information can result in the quantification of a performance indicator for one strategy, but not enough to quantify the other three strategies, which makes it difficult to assess the strategy altogether. This can even lead to misjudgment because a partial quantification can influence the comparison of the strategies, indicating higher or lower performance. A trade off between the available information and level of quantification needs to be made.

The simplification of the coastal system analysis has the biggest implication for the certainty of the working principles of the sediment management methods. The working principles are based on coastal system characteristics and hydro dynamic processes. Uncertainty in these principles reduces the efficiency and potential of the sediment management strategy significantly. However, various potential strategies can still be assessed with the tool in the preliminary design stage. The sensitivity analysis in the tool decreases the uncertainty in the assessment. This analysis makes it possible to analyse the sensitivity and stability of the results of the assessment and identifies the second best strategy for the case study. With this analysis, the different strategies can also be assessed focusing on one category. This creates the opportunity to focus on the most uncertain aspects and see which strategy will perform best. The assessment of the effectiveness gives an extra insight into the performance of the strategy and a weight score. If the uncertainty of the effectiveness is high this score can be used to identify the most suitable strategy. These two extra analysis reduce the uncertainty of the total assessment and support the decision making process towards a sustainable sediment management strategy.

In conclusion, the tool can be used to find a sediment management strategy for every port in the world and for different stages in the port project. The tool is applicable to grow and develop within the port project stages. The current tool has its limitations but there are opportunities for further development and case specific additions.

7

Conclusion and recommendation

This chapter describes the conclusions and recommendations of the research project and thesis. The conclusions are structured around the derived sub-objectives of this research project, ultimately forming the conclusion to the main objective. The conclusions will be followed by recommendations for further research and advice to Arcadis.

7.1. Conclusion

This section describes the conclusions of the research project and thesis. The main objective of the research is stated below. To obtain this main objective, the research focused on five different sub-objectives. These served as a guide through the research project obtaining the result of the main objective. To come to the conclusions of the research, the subsequent (sub)objectives will be repeated.

Main objective Explore potential dredging and sediment management strategies to optimize sediment management in the port towards more sustainable methods, develop a decision-making tool and apply the tool in a specific case study.

There are various potential sediment management methods to optimize sediment management for more sustainable port maintenance. A structured decision-making approach supports the process towards a suitable sustainable sediment management strategy. The decision-making tool can assess several potential sediment management strategies and make preliminary design decisions.

1 - Map the current state of dredging techniques and strategies for port development projects and compare each technique's strengths, weaknesses, and opportunities.
Currently, there are various methods to manage sediment in a port. Several examples show potential to improve and optimize the maintenance strategy towards more sustainable methods. Various techniques have the potential to be used in these strategies. Furthermore, it is important to consider dredged material as a valuable resource with great potential to the port and the coastal system instead of a waste.

2 - Define the potential of various sediment management methods for sediment management strategies.
Several management approaches exist considering more sustainable management. The waste hierarchy, adaptive management, and the design of sustainable infrastructure approach have the potential for improving the sustainability of sediment management. A sediment management hierarchy is obtained from the waste hierarchy considering the steps; Prevent and Reduce, Reuse and Recycle, and Disposal. Various prevention, reuse and recycle methods and examples indicate a potential for more sustainable sediment management. This research mainly focuses on the implementation of prevention methods. The ten prevention methods with great potential for sediment management are:

- Sediment trap

- Sediment bypass system
- Habitat creation
- Blocking structure
- Blocking screen
- Guiding structure
- Natural sediment bypassing
- Resuspension device
- Fluid mud
- Bed levelling

With these prevention methods, sediment management can be optimized towards more sustainable strategies as part of the sediment management hierarchy. In conclusion, the use of the sustainable sediment hierarchy considers the value of sediment and dredged material creating opportunities for a more sustainable maintenance strategy of a port.

3 - Create a decision-making approach and tool that provides insights into the different possible sediment management strategies, making it possible to choose the most suitable strategy for specific port development.
A decision-making approach is developed based on port case studies, expert interviews, sediment management challenges, and literature on management and design approaches. The developed decision-making approach providing insight into different possible sediment management strategies consists of four steps:

1. Sediment management objectives - analysis of the current state of the system, maintenance, and sediment management;
2. Fit to case - pre-assessment of possible prevention measures for the sediment management strategy;
3. Assessment of potential strategies - assessment of the potential sediment management strategies for the port with the decision-making tool;
4. Meeting the objectives - long-term sediment management and maintenance strategy for the port.

The approach supports the decision-making process towards a sustainable sediment management strategy. The performance indicators in the various categories are used to assess the potential strategies. A complete assessment can be obtained by using a performance indicator from each category: *Reduce, Financial, Operational, Resources, Environmental, Community,* and *Durability*. By using these categories, all the important aspects of sediment management are considered and taken into account in assessing potential strategies. The uncertainty is minimized by means of sensitivity analysis and the assessment of the effectiveness of the prevention method. There are some limitations to the developed decision-making approach. However, it considers all main aspects to find a preliminary design of a sediment management strategy for a port using a structured approach.

4 - Perform a case study for an existing or newly developed port and develop a sediment management strategy for the specific case based on pre-selected performance indicators and reflect on the results
In chapter 4 a case study is performed on a port in Porto Amboim. The case study supported the development of the decision-making approach and tool. For the case study, suitable sediment management strategies are obtained with the approach and tool. These strategies are obtained with an assessment in the decision-making tool using twelve performance indicators considering all the important aspects of sediment management for this case.

In the reflection the available information, the potential strategies and the proposed strategy for Porto Amboim are described. In conclusion, despite the uncertainties in the case study two suitable more sustainable sediment management strategies have been obtained with the available information. The developed decision-making approach supports the process of obtaining and assessing several potential strategies because it considers all aspects of sediment management and analyses the impact on the environment and benefits for the community. In the next phase of the port project, a more detailed design and analysis of the coastal system will lead to the final sediment management strategy for the case, Porto Amboim.

5 - Validate the decision-making approach and tool and assess the generic applicability of the decision-making approach.
The validation is performed with a case study on the Tweed River Entrance and an expert session. The validation showed a potential for the generic use of the decision-making approach and tool because of the applicability in three different case studies. The Tweed River Entrance assessment showed the potential to perform a quick assessment with little information and performance indicators in each category. The expert session showed that some prior knowledge is required about the prevention methods and coastal response to make a quick assessment. However, the tool provides a good overview of all the methods and support the decision-making process to find potential and suitable strategies. It can be concluded that it is a useful approach to apply in the primary design phase. The tool can be used to find a sediment management strategy for every port globally and at different stages in the port project. The current tool has limitations, but there are (several) opportunities for further development and case specific additions.

The minimum data that is needed to apply the decision-making approach and perform an assessment is listed below. These minimum input requirements are based on the literature review and case study outcomes. With this data available, a viable and reliable assessment can be performed. A quick assessment gives insight into the potential sediment methods, resulting in a preliminary design of a sediment management strategy for the specific port.

- Port operations
- The littoral drift and wave direction
- Sediment transport patterns
- The involved stakeholders
- The environmental conditions
- The current sediment management strategy

The current tool is suitable for generic use in the preliminary design phase of a sediment management strategy. The results of the assessment with the tool give a suitable sediment management strategy. In the next phase, this strategy needs to be developed and designed further towards a final design. Furthermore, the tool can be developed further to be applicable in other design stages of the process. More details can be included to perform a more extensive assessment, and the tool can grow with a project.

By means of evaluating the five sub-objectives, it can be concluded that there are several methods to optimize sediment management in ports towards more sustainable methods. The developed decision-making approach supports the process to a sustainable sediment management strategy in a port because it considers all the important aspects of sediment management within the various categories, it considers all the potential sediment management methods, it is suitable to perform a quick assessment of several potential strategies, and it is applicable on every port study.

7.2. Recommendations

This section provides recommendations for further research on optimising sustainable sediment management and recommendations for Arcadis on the application and further development of the tool.

Recommendations for further research

As dredging is always involved in the sediment management strategy, it is recommended to further investigate the optimization of the dredging process and include more sustainable measures. There is still a lot of potential innovations in the dredging industry. Aspects to consider are reducing emissions, optimizing the dredging cycle, recycling of equipment and materials, adaptive management of the dredging process, and making a transition to more renewable energy sources. More research into these topics will enhance sustainable sediment management.

Considering dredged material as a valuable resource instead of waste has great potential. Dredged material can be used in different ways for engineering purposes, environmental enhancement or as raw material. It is recommended to obtain further research on the potential ways to reuse and recycle the dredged material to optimize this process, as it is a valuable resource. Dredged material will always be part of a sediment management strategy and reusing all the material can lead to a 100% circular strategy.

Sediment management starts in the design phase of a port. This research mainly focused on optimizing sediment management in existing ports. Considering the sediment transport patterns along a coastline of a new port in an early stage creates the opportunity to adjust the port's location beneficial for sediment management. Also, in the detailed design phase of a new port, small adjustments in the design can have favourable effects on the sediment transport patterns optimizing sediment management. It is recommended to consider these opportunities in the design phase of a port project to optimize sediment management in an early stage. Investigating the extra aspects or factors important in the decision-making process for a sediment management strategy in a new port will give insight into the suitability of the tool to apply in this design process. Also, it will identify how to further develop the tool to use in new port projects.

Advice to Arcadis

The tool is suitable to grow with projects and has great potential to be used in various project stages of a port project. In this research, the tool was limited to sediment management and mainly to the preliminary design stage. It is recommended to investigate the suitability of the tool for a broad application within Arcadis. The tool has the potential to be further developed to use with clients, for example. It is recommended to identify the client's needs and adjust the tool to their needs to discuss potential sediment management strategies.

As mentioned, it is recommended to quantify the performance indicators further. More quantification of the environmental aspects and emissions creates the opportunity for a more extensive assessment of the potential strategies. More data is, for example, needed on environmental aspects or coastal response of the case study and strategy to perform this quantification. Using the tool in upcoming port projects gives insight into the needed data and stimulates the further development of the tool. It is interesting to consider the tool's possibilities in all design stages and use it on a port project basis. This results in the further development of a comprehensive and convenient tool.

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A

Prevention measures: application and projects

There are several methods to prevent sediment from entering the port and/or reduce the siltation in a port area (Winterwerp (2005), Kirby (2011), van Rijn (2016)). It is important to identify all the different possibilities and find the most suitable measure for each individual port. Complete prevention of sedimentation is ideal but very difficult to achieve. However, several measures are capable of reducing the sedimentation rate significant. This appendix further describes all the prevention measures and gives examples of applications and projects.

The prevention measures described in this chapter are divided into three categories *sediment control* (A.1), *reducing structures* (A.2), and *resuspension of sediment* (A.3). Sediment control discusses the sediment managing options controlling the location and accumulation process of the sediment. The section, reducing structures, describes various structures blocking or redirecting sediment, reducing the inflow of sediment. The last section describes several ways to resuspend the sediment to decrease the sedimentation rates. The methods described in these different categories address three principles (Kirby, 2011):

- **Keep sediment out (KSO)** keeping sediment out of the area of interest that might otherwise enter and accumulate.
- **Keep sediment moving (KSM)** raising flow velocities in the port area to prevent sediment from settling as it is transported through and out of the area of interest.
- **Keep sediment navigable** keeping the sediment navigable in the area of interest, applicable to sites characterised by high turbidity near-bottom sediment regimes and muddy beds.

A.1. Sedimentation control

This section describes methods to control sediment and stabilise the sediment source in the area of interest. An area is created or a measure is taken to control the accumulation location or natural sediment flow. In the proposed methods the principles Keep sediment out and Keep sediment moving are both applied. The prevention measures aim to extend the period between two dredging campaigns. This is achieved by controlling the location of the settlement and/or moving the sediment, resulting in more controlled sediment management.

Sediment trap

A sediment trap is a storage place for sediment to accumulate before dredging. Sediment traps can be located inside the port's basins and channels or outside the port. A dredged trench, the trap, reduces flow velocities in the above water column and therefore decreases the capacity to transport sediment, which results in sediment settlement. The sediment is stored in the trap at a specific location. This method does not generally decrease the volume of dredged material required, but it can reduce the unit cost of dredging by avoiding interference with navigation during dredging operations, shortening the distance to the disposal area or reduce the need for dredging in difficult to reach areas.

Application and projects

The sediment trap allows focusing the dredging activities in a specific location of the port area rather than everywhere in the port. Storage outside the port area reduces the sediment entering the port-channel and basins. In a study on the marina *Le Rochelle,* (Huguet et al., 2020) a reduction of siltation up to 62% is obtained. To optimize the efficiency of a trap the balance between the size, depth, and location of the trap have to be carefully determined. This balance controls the trapping efficiency of this measure.

In the port of Rotterdam, a few sediment traps are constructed to trap fluid mud in the port (Tempel, 2019). In a pilot project, water injection dredging (WID) is used to create fluid mud Kirichek and Rutgers (2020). The sediment trap captures the fluid mud in the Calandkanaal and reduces the need for regular maintenance dredging in the area. With this measure, the cost and emitted CO_2 can be reduced significantly.

Potential for sustainable sediment management

The high trapping efficiency and controlled area of accumulation of this method make it an interesting method for efficient sediment management. The method can be applied to keep sediment out or reduce the time between two dredging campaigns. It is important to identify the capacity of the sediment trap and make an assumption about the trapping efficiency.

- Challenges
  - Not reducing the total volume that needs to be dredged
  - Difficult to predict its efficiency
- Potential
  - Traps the sediment before entering the port
  - Keep sediment out
  - Sediment settles on a controlled location
  - Extends the period between to dredging campaigns.

Sediment bypass system

The general concept of a sediment bypassing system is passing the sediment by a port entrance or river mouth with an installed jet, suction, and pump system to contributing to the littoral drift. The sediment is caught at the upstream side and deposit at the downstream side of the bypassed area, where it can continue in its natural littoral drift direction. A bypass is generally constructed to overcome the interruption of the littoral drift by a river or port entrance. Sediment bypass projects generally have two main objectives:

- Maintaining the navigability of the bypassed area, preventing sediment from accumulated and move in the channel or port.
- Nourishing the adjacent coastline at the downstream side of the bypassed area.

Application and projects

There are a few examples of successful operating sediment bypass systems around the world. Most of the systems can be found along the Australian East coast and some in the United States. The main objective of bypassing sediment can be obtained in multiple ways with a jetty with multiple suction pipes or a crane mounted suction head.

One example of a large and successful sediment bypass project is the *Tweed River Entrance Sand Bypassing Project* in New South Wales (NSW) and Queensland, Australia. The main objectives of this project are maintaining the navigation channel in the Tweed River and the southern Gold Coast beaches. These goals are obtained with a fixed sediment bypass system south of the Tweed River entrance and maintenance dredging activities in the Tweed River entrance area. The system consists of eleven jet pumps installed on a 450 m long jetty. The maximum pumping capacity of the jetty is 500 m^3 per hour, this rate is obtained when four pumps operate simultaneously (Cox and Howe, 2012). The annual transport rate varies from 250,000 to 1,000,000 $m^3/year$ (Boswood et al., 2005). The dredged slurry is pumped via a buried pipeline across the Tweed River to several discharge outlets located along the Southern Glod Coast beaches.

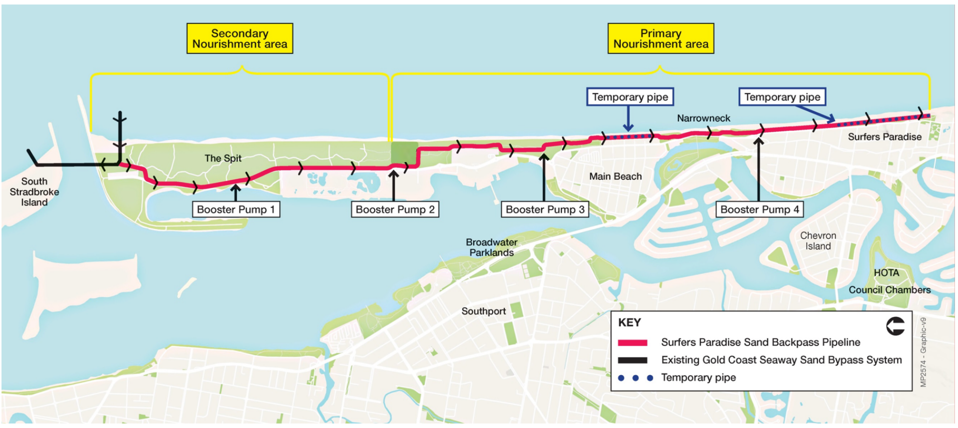

Figure A.1: Surfers Paradise Sand Backpass Pipeline Project (City of Gold Coast, 2020)

A project in construction is the *Surfers Paradise Sand Backpass Pipeline Project*, an addition to the Gold Coast Sand Bypass System (A.1). In this project, a 7.8 km long pipeline is installed to deliver sand from The Spit to nourish the beaches at Narrowneck, Main Beach and Surfers Paradise. The pipe will transport sand from the existing Sand Bypass Jetty at The Spit onto the beaches along the northern Gold Coast. The system will make it possible to maintain the beaches proactively. The pipeline has the capacity to transport up to 20% of the net natural littoral drift, approximately 120,000 $m^3/year$, back to the Gold Coast beaches and operates with four booster pumps (Council of the City of Gold Coast, 2020). This project will protect the Surfers Paradise beaches from coastal erosion and storm events. The four drivers of this project are to improve the loss of beach amenity, the loss of public infrastructure, the damage to the city image and the reputation and the positive impact on tourism and the overall economy of the Gold Coast. The project will be finished at the end of 2021 and start operating under continuous monitoring to proactively maintain the beaches with the sand from the natural system (J. Taylor, personal communication, 17 November 2020).

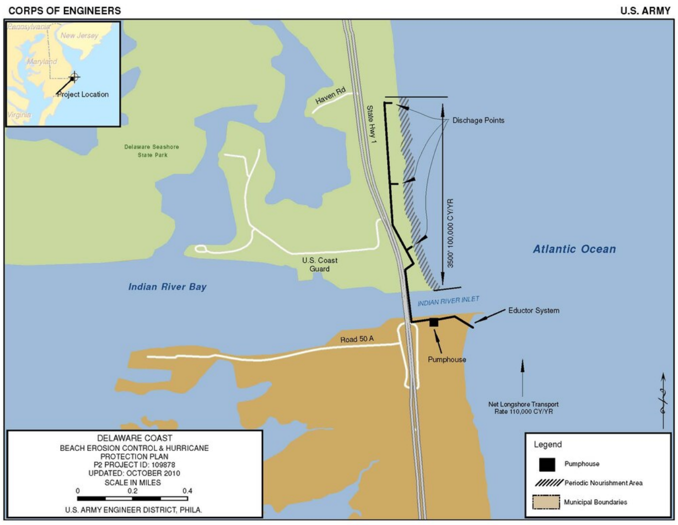

Figure A.2: Sediment bypass system with three discharge points - Indian River Inlet

An other project is located at the Atlantic coast of Delaware near the inlet of the Indian River. The system was constructed to counteract the downdrift erosion caused by the construction of the training walls in 1940. The system was designed based on the requirement to transport 84,000 $m^3/year$ from the up drift side to the downdrift beach side of the inlet. The system (Figure A.2) consists of a crane mounted suction head connected to a pump house to pump the slurry via a discharge pipeline across a bridge to the other side of the inlet (Keshtpoor et al., 2013). There are three discharge points on the north side of the inlet. This mobile system is in operation since 1990 and maintaining the beach around the Indian River Inlet.

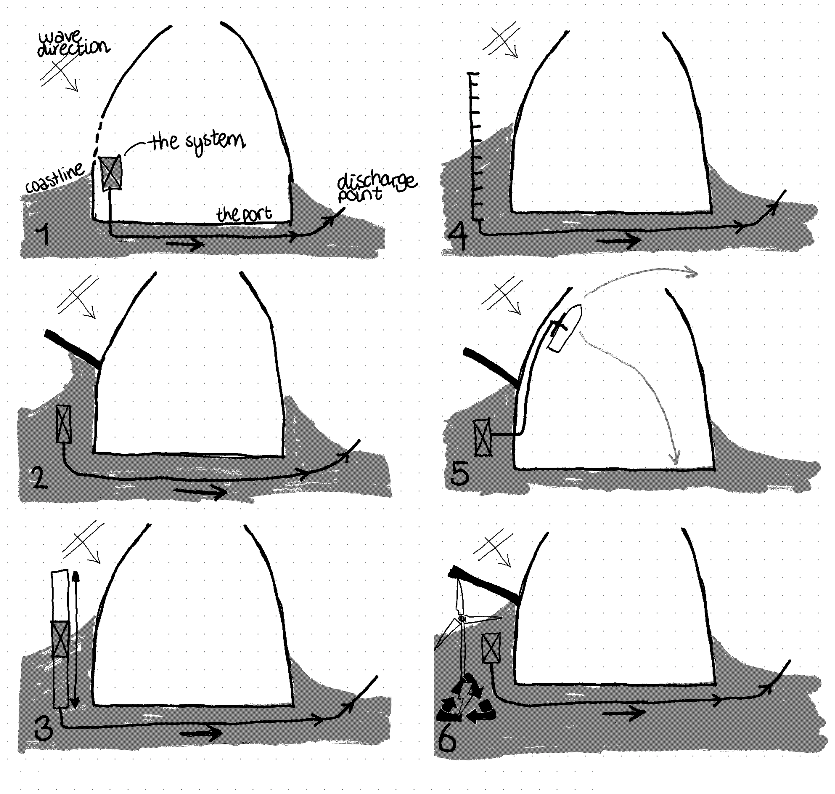

Figure A.3: Six configurations of sediment bypass systems in a port. 1. A port with a SBS inside the port, behind a permable breakwater. 2. A port with a SBS at the updrift side of the port and a offshore breakwater. 3. A port with a portable SBS on in a trestle at the updrift side. 4. A port with a SBS jetty at the updrift side of the port. 5. A port with a portable SBS at the updrift side of the port, a offshore breakwater and a discharge point inside the port. 6. A port with a SBS at the updrift side of the port driven by 100% renewable engergy.

Potential for sustainable sediment management
A good designed sediment bypass system fit to the port's characteristics has the potential to optimize the sediment management in the port.

- Challenges
  - High investment cost
  - Frequent maintenance and monitoring needed during operation
- Potential
  - Keeps sediment out and bypasses it around the port
  - Manages the longshore sediment transport
  - Maintains the sediment balance in the downstream area

Habitat creation

Habitat in the surrounding areas of the port promotes the accretion of sediment away from the port in the habitat area. Mangroves, saltmarsh and seagrass are suitable plants to place in such habitats, they enlarge the trapping efficiency in these areas. Creating or restoring habitat in the port area can reduce the amount of sediment entering the port.

Application and projects
The vegetation lowers the hydrodynamic load from the currents and the waves in the coastal zone. The low dynamic environment which arises in the vegetated habitats is attractive for sediments to settle and stabilise. A more stable sediment environment reduces the amount available for resuspension and therefore reduces the amount of sedimentation in the port, KSO. Increasing habitat has a positive

impact on the environment and biodiversity of the port area. The major uncertainty of this method is to determine the trapping efficiency of the habitat, and thereby the sediment reduction in the port. Often the habitat needs to be large of a scale to have noticeable effects. Habitats are interesting options to consider in sustainable sediment management, as this environmental enhancing measure can have positive effects on sediment stability.

Potential for sustainable sediment management
The stabilisation of sediment and the positive impact on the environment are making this measure interesting for sustainable sediment management.

- Challenges
  - Difficult to predict its efficiency
  - Often a large area of vegetation is needed to be efficient
- Potential
  - Gives an additional ecological value to the port surroundings
  - Keep sediment out by trapping it in the vegetation
  - This is a nature-based solution

A.2. Reducing structures

This section describes methods to reduce siltation in the port area by the principles of Keeping sediment out and Keeping sediment moving. To obtain this a structure needs to be placed in the port area, an invasive mitigation measure with beneficial effects in the long term. Different possibilities and examples are described in this section. A short explanation of the method gives insides in its characteristics and application options are discussed with several case studies to identify the potential for sustainable sediment management.

Blocking structure

Sediment flows occur mostly in the lower part of the water column in the nearshore zone. Preventing this flow from entering and diverting the flow from the port area can reduce the port siltation significantly. A way to block this flow is to place a structure like a sill or a bar near the entrance of the port. The sill blocks and reflects the flows of the lower part of the water column from the port entrance. The placement of the sill needs to be investigated very accurately because a small adjustment can completely mislead the flows resulting in non-beneficial reduction.

Another potential blocking structure already comes quite often with a port. In this structure, the breakwater is constructed to create a sheltered area and protect the port against high wave impacts. The placement of this breakwater can be crucial for the sediment transport and erosion and sedimentation patterns in the port area. Often quite some sedimentation occurs on the exposed side of the breakwater, see Figure A.4. Sediment gets trapped in this area before it travels further to the port entrance channel. The trapping character of this breakwater can be used beneficially to trap more sediment and preventing it from flowing into the port. Identifying and using this positive trapping in an early stage creates a potential for sustainable sediment management.

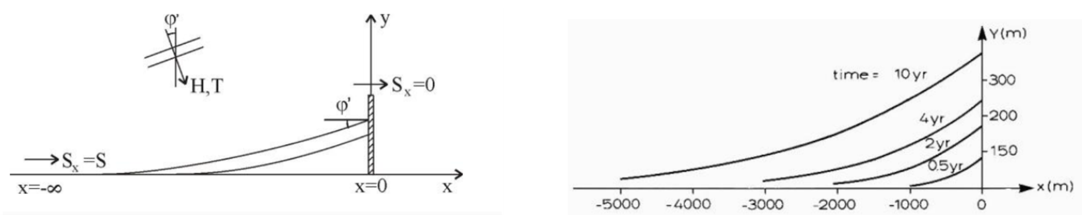

Figure A.4: Accretion of the shore near a breakwater at different times. The wave conditions given in the sketch refer to the conditions at the assumed horizontal part in the coastal area (Bosboom and Stive, 2015).

Application and projects
There are several ways to use this trapping character of the breakwater. The breakwater design can be optimized to create an efficient sediment trap before the port entrance. It is more beneficial to dredge the material from this location then letting the sediment enter the port and dredge the material

in the port. The breakwater creates the possibility to control the sediment flow and management the sediment in a specific location. It is important to identify different configurations of the breakwater to find the most effective configuration for the port. Extension in the longitudinal and lateral direction can have different impacts on the sedimentation and sediment bypassing into the port entrance. The optimal configuration, required for accurate sediment management can be found through carrying out modelling test of the system and sediment flows.

Potential for sustainable sediment management
As the blocking structure reduces the sediment flows into the port and traps or blocks the sediment before the port, it is a measure that can be used in a sediment management strategy. It is a measure interesting to consider if there is one sediment transport direction dominating in the port.

- Challenges
  - Hinder for navigation
  - A large structure to constructed
  - Monitoring required to see its efficiency
  - Difficult to dredge buffer near the breakwater
- Potential
  - Keep sediment out and moving
  - Control of sediment in a specific location
  - Blocking sediment and reflecting sediment from the entrance

Blocking screen
A blocking screen acts as a physical barrier between the port or basin entrance and the surrounding area. The barrier functions as it blocks the sediment from entering the port, while still allowing vessels to pass. Examples of such barriers are silt screens, bubble screen or even a gel screen has potential.

Application and projects
A blocking screen with these properties is the air bubble screen. An air bubble screen is generated by pumping air with a compressor through a perforated hose on the seabed. The bubbles escaping from the holes create a bubble wall while rising to the surface, the physical barrier. The air bubble screen experiment in the Port of Genoa (Cutroneo et al., 2014) identified the potential of an air bubble screen in a low dynamic environment. A circular vertical flow pattern with the potential to retain suspended sediment within an enclosed area was obtained (see Figure A.5). The sensitivity of the air bubble screen to environmental variability was confirmed with a malfunction during strong wind conditions.

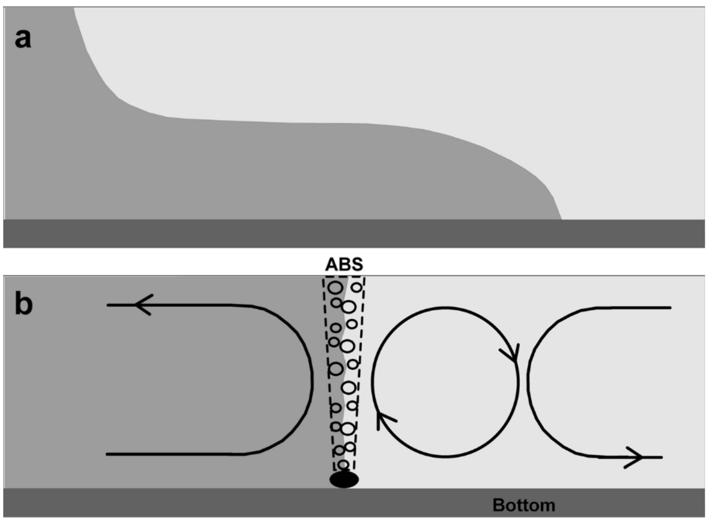

Figure A.5: Circular vertical flow generated by an air-bubble screen (ABS) in case of a density flow (a). The ABS in the water column is indicated with a dotted area of bubbles. (Cutroneo et al., 2014)

The application of air bubble screens in larger ports have not been successful so far. Large-scale and expensive experiments with air bubble screens have been undertaken in NW European ports sited on shallow muddy estuaries, Rotterdam, Hamburg and Antwerp. None of these experiments has proved effective (Kirby, 2011).

A new idea, the gel screen, has gain research interest. The gel screen has the same beneficial properties as the air bubble screen. Sediment flows can not pass the gel and will be blocked when entering a certain area. Vessels can pass through the gel, because of its flexibility. This method is still very new and needs to be investigated first before its potential can be defined.

Potential for sustainable sediment management
As a blocking screen can function as a physical barrier for sediment it has potential to be used in sediment management strategies.

- Challenges
  - An expansive structure
  - Needs to be in operation continuously
  - High energy demands and emissions levels
  - No information about the gel screen, proof of concept
  - Sensible for environmental variability
- Potential
  - Blocks the sediment from entering the port
  - Vessels are able to pass the barrier
  - Keeps the sediment moving and out due to the vertical circulation

Guiding structure

Keep sediment moving (KSM) and Keep sediment out (KSO) is the principle behind this method. Training walls, sills and other diverting structures are placed to guide currents and increase circulation in the port. The structures prevent the sediment from settling or redirected the flow away from the port. This method is often used in rivers and at a river mouth, but also suitable for port entrance channels.

Application and projects
Guiding structure can be constructed merged or submerged outside of the port or at the entrance of port basins. These structures can be applied in different ways, sizes and shape. It is important to analyse the sediment flow in the port in detail to find the best fit solution and guiding structure. There are various different configurations of guiding structures possible and suitable to reduce the siltation in the port. Things to consider when going for these prevention measures are the amount of increased flow, the possible hinder for navigation and the scale of the structure.

A current deflecting wall (CDW) is a guiding structure near a port head preventing fine sediment from entering the port basin using the strategies KSO and KSM. A CDW can passively alter the water exchange and influences the current during high tide. A sill constructed at the bottom deflects the near-bed density currents away from the entrance back to the river or sea. A schematic illustration of a CDW in a tidal port is given in figure A.6. The aim of the CDW is to reduce the density-driven exchange flows. The largest reduction in exchange flow occurs in the lower 25% of the water column. An example of a CDW can be found in the port of Hamburg. The CDW has the potential to reduce the siltation up to 40-50% (Winterwerp, 2005).

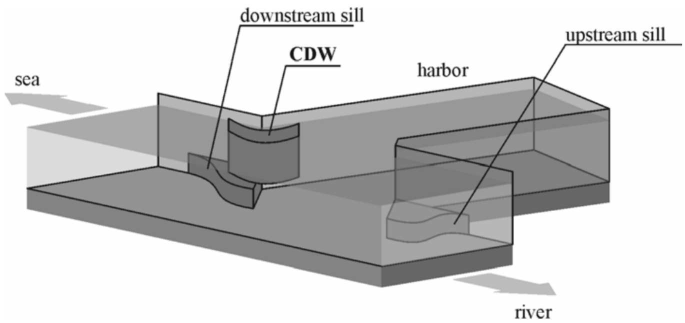

Figure A.6: Current Deflecting Wall downstream a tidal river, port entrance (Stoschek et al., 2003)

CDWs can also be placed in other parts of the harbour basin to avoid dead areas and keep sediment moving, KSM, through the basin (Stoschek et al., 2003). A difficulty of the CDW is that every CDW needs to be design specific for its location. A same inaccurarcy in the design can change the flow pattern completely and will influence the possitive effects. This designing requires a lot of modelling and takes time. An other disadvantage is that the CDW is experienced as an obstacle for safe navigation. Accurate stakeholder management is required to constructed a CDW safe for navigation. All the aspects are important to assess when considering this approach for sustainable sediment management.

Potential for sustainable sediment management
A well designed guiding structure can stimulate the flow and sediment patterns in the port area. This enhances the sediment transport rate and decreases the accumulation of sediment making this method interesting for sediment management.

- Challenges
  - Needs an optimized design for the specific location
  - Hinders navigation
  - Maintenance needed
  - Large structure
- Potential
  - Keep sediment out
  - Keep sediment moving
  - Interacts with the natural flows and tidal currents
  - Deflects the sediment from entering the port

Natural sediment bypassing

Natural sediment bypassing can be increased in ports due to the construction of well-designed breakwaters. Two streamlined breakwaters located at the port head increase the bypass of sediment past the harbour head by increasing the flow velocity due to contraction around the head. The increased flow bypasses the sediment around the harbour head.

Application and projects
A good design harbour head can have a positive influence on the natural bypassing process but there are difficulties to obtain this. An optimum has to be found in the relation between maintenance dredging, natural depth, and navigation depth for every single case. This conclusion was obtained in the study (Mangor et al., 2010) on the bypassing mechanisms of harbours in a littoral transport coast. Both short and long term morphological changes have to be considered and are of large influences on the efficiency of the sediment bypassing. As first the sand accumulates at the upstream side of the breakwater due to the blockage of the port. After some time the bypassing starts and sand is bypassed around the breakwater heads driven by the contracted flow, figure A.7.

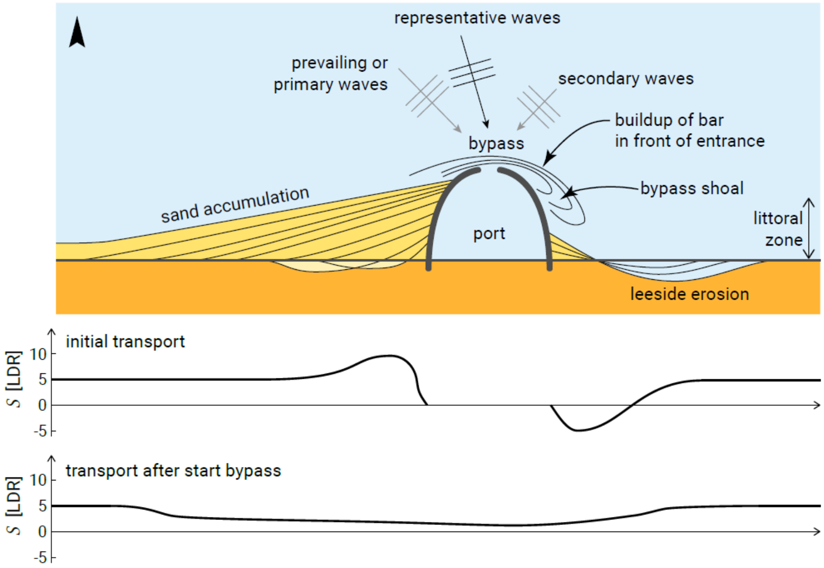

Figure A.7: Schematic shoreline development, morphological development and net littoral drift budgets (in unspecified of Long-shore Drift Rate (LDR)) for a port at a coast with a slightly oblique resulting wave attack.

An example of a bypass harbour is the Hvide Sande Harbour (Hillen et al., 2009). In this harbour, two new protective breakwaters are constructed together with an up drift capital dredge of the coastline. The application of the streamlined breakwaters increases the bypass of sediment past the harbour mouth by increasing the flow velocity due to contraction. The retreat of the coastline helps to maintain the required additional water depth. The purpose of this project is to create a sufficient navigation depth at the harbour entrance and improve the natural bypass of the littoral drift. It is interesting to assess this approach in ports with a strong littoral drift and a navigation depth quite similar to the natural depth.

An other example of bypass harbour is the Hanstholm Harbour located at a headland on the northern part of the Jutland coast. At this harbour the symmetrical and streamlined layout creates a convergence of the flow transporting the sediment by the harbour head and entrance area of about 9m depth. The flow is mainly driven by meteorological forcing, variations in wind and pressure, and, to a smaller extent, wave breaking. The layout of this harbour is optimize with physical modelling techniques to obtain minimum sedimentation and maximum natural bypass. The combination of factors creating this good bypassing conditions are (Mangor et al., 2010):

- The location at a headland, which causes additional meteorological driven currents which accommodate bypass and a large natural depth,
- The streamlined layout of the breakwaters,
- The vertical face of the breakwaters, and
- The oblique wave climate.

Potential for sustainable sediment management
If the right balance is found between the maintenance dredging, natural depth, navigation depth, and littoral transport this strategy is interesting for sustainable sediment management. Stimulating the natural bypassing of sediment can play an important role in maintaining the sediment balance in the port area and can decrease the need for regular maintenance dredging, making it interesting to consider.

- Challenges
  - Requires optimal and intensive design
  - Large structure
  - Monitoring required to indicated when bypassing rate reduces and dredging is needed
  - Not efficient if large nautical depths are required
- Potential
  - Bypasses the sediment around the port entrance naturally
  - Keep sediment out
  - Makes beneficial use of the natural drift and improves the sediment balance

A.3. Sediment in suspension and resuspension of the sediment

In this section, methods are discussed to keep sediment in suspension and resuspend the sediment. The different methods aim to keep the sediment moving (KSM) and keep sediment navigable (KSN) to reduce the need for maintenance dredging. For these methods still, mechanical devices are needed but these devices can operate more efficiently and with fewer emissions compared to maintenance dredging. The methods aim to replicate the regular natural resuspension of recently deposited bed sediment to prevent ongoing siltation.

Resuspension of sediment

An increased bed shear stress keeps the sediment moving and in suspension. Devices that can be used to adopt this approach are hydraulic jets, propellers, vortex foil arrays and mechanical agitators. Attaching the devices to quay walls or placing them on the seabed generates currents resuspending the sediment and keep the sediment moving. The resuspended sediment flow can be transported out and away from the port with the tidal and gradient currents.

Application and projects

The devices used for the measure keep the sediment moving or bring the just accumulated sediment back in suspension. This reduces the total sedimentation rate. In the United States, fixed position jet and propeller arrays have been used in berths where high rates of sedimentation occur carrying the suspended sediment away with strong currents. This method is interesting to assess as it can be beneficially used to maintain navigability in specific areas of the berth.

In the port *Marina of Cervia*, Italy, the effectiveness of an ejector plant to manage the sediment is assessed (Pellegrini et al., 2021). Submersible jet pumps, ejectors (see Figure A.8), are installed at the port entrance to guarantee a minimal water depth. The ejector plant removes settling sediment in the entrance channel of the port. This demo plant shows the potential to manage sediment at a port entrance with a ejector plant.

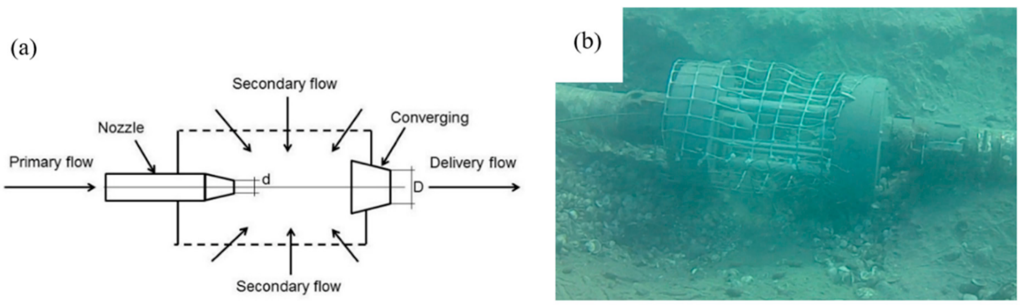

Figure A.8: (a) Sketch of the ejector device (b) The ejector in operation (Pellegrini et al., 2021)

Potential for sustainable sediment management

Stimulating the sediment flow, creating a navigable fluid mud layer or use devices to remove the settled sediment make this prevention measure interesting for sediment management. Especially for port were high concentrations of fine sediment occur or a small area needs to be maintained is this an interesting method, decreasing the need for regular maintenance dredging.

- Challenges
  - Needs to be in operation continuously to avoid sediment accumulation.
  - The system or devices have high energy consumption.
  - Could influence the navigation safety near the installation.
  - Possible hinder or interaction with the port operations.
- Potential
  - Keeps the sediment moving in the port.
  - Decrease the amount of needed maintenance dredging.
  - Keeps the sediment navigable and increases the nautical depth.
  - Removes the sediment from the channel

Fluid mud

Another principle with potential is navigating through fluid mud. This method creates a fluid mud layer through which vessels can sail, *keep sediment navigable*. Water injection dredging (WID) is used in ports to resuspended sediment, stimulating sediment flow out of the port and creating fluid mud layers. The density properties of fluid mud allow vessels to sail through the mud enlarging the nautical depth of the port's channels and basins. The main principle of this method is:

- Create a fluid mud layer with a resuspension device or dredge.
- Increase the nautical depth with a fluid mud layer through which vessels can sail.

Application and projects

To a certain depth, it is possible for the vessel to sail through mud, KSN. If the mud is kept in suspension, reduced density, the channel will be navigable. The nautical depth is obtained if the distance from the water surface to a given wet density is sufficient according to the port guidelines. This wet density typically ranges from 1,100 to 1,300 kg/m^3 (Kaveney et al., 2017). PIANC follows this in its nautical bottom applications with levels of 1,200 kg/m^3 and 100 Pa to estimate the nautical depth (Kirichek and Rutgers, 2020). Methods that can be used to keep the mud in suspension are hydraulic jets, water injected dredgers (WID) and propeller wash from vessels. It is interesting to identify the beneficial use of fluid mud to optimize the dredging strategy of the port are. Fluid mud has been shifted from a pernicious, unwelcome waste to a valuable resource with a beneficial use (Kirby, 2011) and increase the nautical depth (figure A.9).

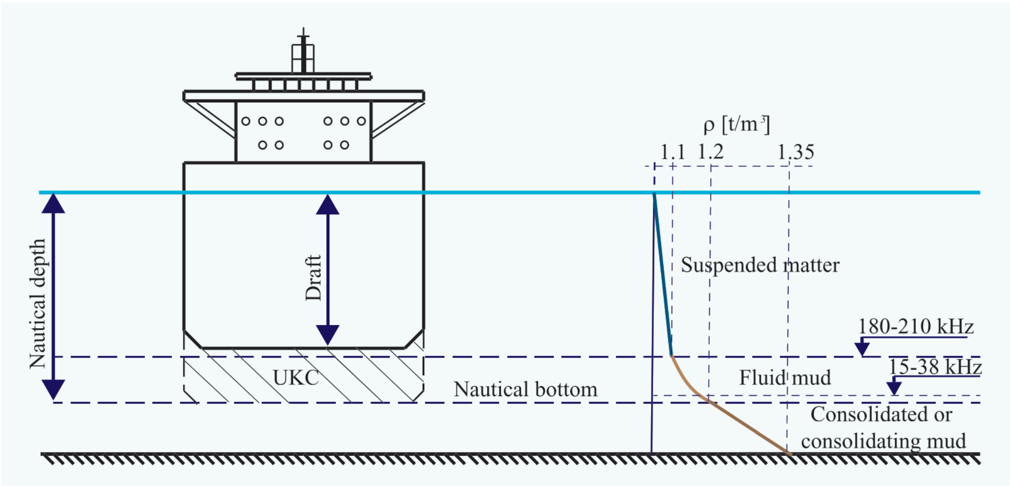

Figure A.9: The nautical depth concept, Kirichek et al. (2018)

The project in the Calandkanaal in the Port of Rotterdam investigates the potential of WID and the beneficial use of fluid mud. In the program *PRISMA* (*PRogramma Innovative Sediment MAnagement*) the Port Authority looks into new dredging methods and how sediment reacts to these techniques. The purpose of the program is to improve the maintenance dredging and reduce CO_2 emissions (Port of Rotterdam, 2020). In the pilot in the Calandkanaal is determined that the WID is more CO_2 efficient than regular maintenance dredging with a TSHD, with a CO_2 reduction of 45-64% during the total duration of the pilot (Kirichek and Rutgers, 2020). Other benefits where a reduction of the costs and less hinder of marine traffic during the dredging operations due to the change in dredging equipment, from TSHD to WID. Making use of the beneficial properties of fluid mud is an interesting approach to consider sustainable sediment management.

Potential for sustainable sediment management

Fluid mud is interesting for sustainable sediment management in large ports with fine sand and silt. The increased nautical depth (Figure A.10) obtained with WID decreases the need for maintenance dredging. A balance between the dredging methods and the interaction with the vessels need to be found to obtain a good sediment management strategy with fluid mud.

- Challenges
  - Difficult to predict the exact nautical depth in the fluid mud.
  - Trust in fluid mud of the sailors needed.
  - Monitoring of the fluid mud layer needed to ensure the required depth.
- Potential
  - Keeps the sediment moving.
  - Decrease the amount of needed maintenance dredging.
  - Keeps the sediment navigable.
  - Reduce the total CO_2 impact, as WID is more CO_2 efficient.
  - Beneficially uses the properties and potential of fluid mud.

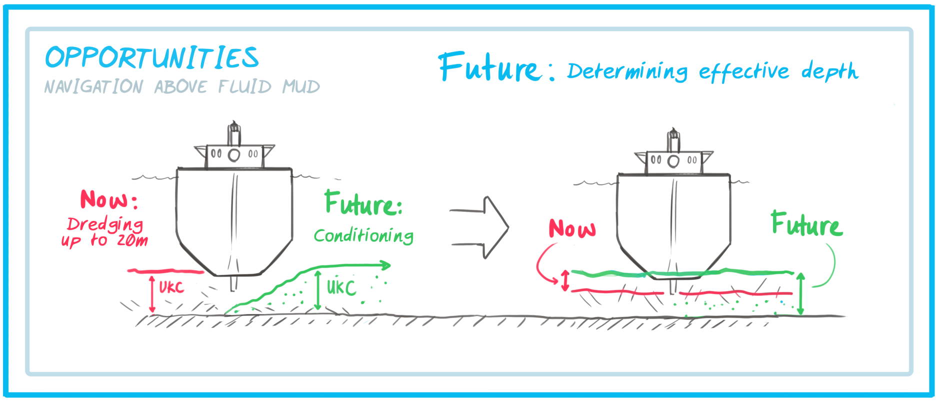

Figure A.10: Sailing through fluid mud (smartport.nl, 2021)

Bed levelling

Drag barring is used to reduce the need for maintenance dredging by redistribution of sediment. During bed levelling or drag barring a heavy metal bar is lowered to a certain depth and dragged across the seabed. This method keeps the bed equally levelled en smooth. Unevenness in the bed increases accumulation rates and causes siltation. The smooth bed keeps the sediment moving and stimulates flows through the port basin. The process can also result in the resuspension of some fine-grained sediment, which if the currents are strong enough will be transported away from the area (Symonds, 2018).

Application and projects

Applying drag barring decreases the frequency of needed maintenance dredging in the long term because of the lower accumulation rates, KSM. The barring is most beneficial in the berth area of the port because mooring ships cause unevenness on the seabed. It is an efficient approach to maintain the navigability in the port between dredging campaigns and can be carried out by the port authority itself. Especially in areas difficult to reach by TSHD bed levelling can contribute to the dredging efficiency.

Potential for sustainable sediment management

- Challenges
  - Needs to be carried out quite often
  - Hinders the normal port operations
  - Limiting to be efficient over certain depths
- Potential
  - Keep sediment moving
  - Decrease the amount of needed maintenance dredging
  - Can be carried out by the port itself
  - Can be used in berth areas difficult to asses

This appendix describes potential methods for more sustainable sediment management. The prevention methods discussed can be applied in port to optimize the sediment management strategy. Considering all the possible options is important to find the best fit strategy for a port.

B

Reuse and recycle: application and projects

To realize sustainable sediment management in a port project, dredged material need to be considered as a valuable resource rather than a waste. This chapter describes various beneficial reuse and recycle options for dredged sediment. The reuse methods are divided in three categories engineering use, environmental enhancements, and product use. The beneficial way of reuse is described and examples of successful projects are given to discuss the potential of the option. Several examples can be found in the case studies gather by the CEDA (2020).

B.1. Engineering uses

Dredged material is reused in engineering projects onshore and offshore. In the section several examples of engineering use are described first onshore recycle options are given followed by offshore reuse. In onshore project the dredged material is mixed or treated before use to meet the engineering requirements. Offshore dredged sediment is often use to support and interact with the natural system, here untreated material is sufficient to use.

Land reclamation

Dredged material can be reused for land reclamation in the ports surrounding area. This option depends on the need for land reclamation in the area. If a suitable site is available using dredged material from maintenance dredging is a sustainable reuse option. However reclamation works are always limited, as it is a project with a deadline and often combined with capital dredging in the reclamation area.

In an expansion project of a port terminal in Oslo contaminated sediment is reused for land reclamation. Material dredged from the seabed is stabilized by mixing with a GGBS plus cement-based binder and used in the construction of a new quay wall for the port terminal (CEDA, 2020). This is a beneficial way to reuse contaminated sediment as a material for land reclamation and reducing the leaching of contaminates into the environment.

Construction fill

Dredged material can be used for construction fill if the sediment properties meet the requirements. Using dredged material instead of fill materials from quarries has a positive impact because of the use of recycled material. The need of construction fill in the ports surrounding area depends on the available projects, the sediment properties and the geotechnical requirements.

Land improvement and elevation

Dredged material is suitable to raise elevation in low-lying areas in the port surroundings. As land subsidence and foodings are issues occurring in coastal river deltas, there is potential need for elevation. Reusing the material in these areas is a beneficial way of material use. Reusing the material counteracts land subsidence. It is important to asses the sediment properties of the material before using on the land, if the material meets the requirements it can be used to improve and elevate the land.

Beach nourishment
Often erosion occurs in the port area, as the port influences the natural sediment balance. This unbalance results in sedimentation upstream of the port and erosion downstream of the port. Beach nourishment is applied at eroded area by placing sand and sediment at the eroded coastlines. Reusing the dredged material for beach nourishment is a sustainable way to maintain the beaches and restore the sediment balance. The dredged material is not always suitable to use for nourishment as the properties of the silt in the port are different from the beaches. It is important to asses the sediment properties of both materials to see if nourishment is possible. The suitable material is then placed in the nearshore zone and upper portion of the beach.

Sediment cell maintenance and berms
Dredging sediment from the port is dredging sediment from the system, resulting in sediment scarcity in the system. A good way to reuse the sediment is to put it back into the system. The sediment sell input should be equal to the sediment cell output. Often offshore disposal sites are identified to obtain this and reallocated the sediment.

Away to maintain the sediment cell is to create berms with the dredged sediments. The primary goal of the berms is to feed the system and protect the shorelines. Berms can be constructed in two ways with different purpose, feeder berms and stable berms. Feeder berms are constructed in shallow, near shore waters and provide a source of sand to eroding beaches, feed the system. Stable berms are constructed in deeper water and reduce the energy in long-period storm waves, shoreline protection (Yozzo et al., 2004).

Shoreline protection and stabilisation
An other way to reuse the dredged material is to use it for shoreline protection. Instead of depositing the material offshore, creating nearshore berms and bars can have positive impact on the shoreline protection. The berms reduce the wave energy near the coast by causing waves to break on the berms more offshore. In this way the shoreline is experiencing less wave impact. This is a potential example to consider as an beneficial reuse option to maintain the system.

B.2. Environmental enhancements

There various options to reuse dredged material to create and restore habitat to enhance the environment in the port surroundings. The material can be used beneficial in several projects onshore, nearshore and offshore. Enhancing the environment is often a part of a port construction project and can be seen as ’giving something back to the nature’.

Creating and restoration of artificial reefs and shoals
The suitable part of dredged material for artificial reefs is rock. Rock material is often found in dredged material but not suitable for placement on beaches. The rocks can be reused for the creation of artificial reefs in the coastal zone. Artificial rock reefs can increase the number of species in the area.

The other part of the dredged material can be used to create shoals, berms, in the nearshore zone. The berms are used for shoreline protection but also function as a beneficial area for fishery and increase habitat value in the nearshore zone.

Restoration of inter-tidal marshes and mudflats
Dredged sediment can be reused to enhance salt marsh development on shallow mudflats. The dredged material is suitable for the salt marsh vegetation to propagate on. A way to establish this is with the ’Mud Motor’ approach. A Mud Motor is a dredged sediment disposal in the form of a semi-continuous source of mud in a shallow tidal channel allowing natural processes to disperse the sediment to nearby mudflats and salt marshes (Baptist et al., 2019). The mud in the currents feed the salt marshes and will accelerate vertical and lateral marsh-growth.

The feasibility of a Mud Moter depends on an assessment of most important additional travel time for the dredger, the effectiveness on salt marsh growth, reduced dredging volumes in a port, and other practical issues. The ecological functions provided by the inter-tidal marshes are also important to consider, functions as shoreline stabilization, surface water and ground water filtration, and provision of nesting/foraging habitat for wildlife (Yozzo et al., 2004).

Creation of bird/wildlife islands
Dredged material can be reused to create islands for wildlife and birds. The islands are constructed using the sand and silt-sand from the dredged material. The size of the islands ranges from less than 1 acre to over 200 acres creating suitable habitats for various species to live on. Islands may be confined using rip rap, wooden cribs or bulkheads, or stabilized with emergent marsh vegetation. In addition to providing habitat for birds and other wildlife, the islands are used for human recreational activities such as camping, hiking, fishing and bird watching (Yozzo et al., 2004).

The Cat Islands Restoration Project is an example of such a project. Three islands are reconstructed providing habitat for shorebirds, waterfowl, amphibians, turtles, invertebrates, and furbearing mammals. The project started with a long wave barrier creating a shallow water and wetland habitat. The three islands will be built with sediment dredged from the outer harbor navigation channel. Each year the dredged material will be added to create the three islands over the coming years, creating new habitat.

Aquaculture
An example of beneficial reusing the dredged material for aquaculture is the restoration of oyster reefs for oyster farming. Areas of interest for this offshore habitat restoration are areas where oysters use to be or are present. The primary method of oyster restoration is to provide hard substrate for larvae to settle upon. The hard substrate is deposit on top of the dredged material, forming the base for the oyster habitat. Typically old oyster shells are used as top layer; however, in some coastal areas this material is scarce and alternatives such as clamshells, concrete rubble, or fly-ash composites are used (Yozzo et al., 2004). Promoting aquaculture with reused material is beneficial for the local community. This potential is something to consider in sustainable sediment management.

B.3. Product use

Sediment is a resource, it can be reused and recycled as a product. Different options are possible because of the varying properties of the dredged material. In this section several options are described and project examples identify the possibilities of the product use of sediment.

The *Pilot Kleirijperij* is a pilot project in the Eems Dollar 2050 and located near the Groningen Seaport in the North of the Netherlands. Main objective of the project is to create clay from sludge. Figure B.1 gives a overview of the pilot project. Several ways and approaches are being investigated to identify all the possible beneficial reuse options of sludge from the Eems Dollard. Examples are; making clay for dikes, elevate agricultural grounds, and making construction materials like bricks. The goal is to create feasible reuse options for the dredged material and sludge from the Eems-Dollard. In the project the ripping process of the sludge is analysed, stimulated, and evaluated (Ecoshape - NL, 2020). This project is a cooperation between several parties and a part of Ecoshape. It is interesting to follow the developments and results of this project because of its potential for beneficial reuse of sludge.

Raw materials
Dredged sediment consists off different raw materials which can be used for various purposes. The dredged material needs to be examined to identify the properties of the resource. In a treatment process the products are separated and dewatered to end up with valuable raw materials.

The METHA-plant (Mechanical Treatment of Harbour-Sediment) in Hamburg is a key technology of the Hamburg Dredged Material Management concept (CEDA, 2020). The plant treats the dredged material from the port for beneficial use, and disposal. Sand, fine sand and silt are dewatered and separated by an aligned technology for each type. This treatment is a good option if large volumes are dredged from regular maintenance. It supports to the beneficial reuse of the material and can guaranty a good product quality.

Construction materials
One of the objectives of the Kleirijperij is to create dike clay from the sludge in the project. In this way the dredged material is beneficial reused as a construction material for dikes. To create a material meeting the requirements for construction the dredged material is often mixed with an other material like a flocculant. The most beneficial way to reuse the dredged material for construction depends on

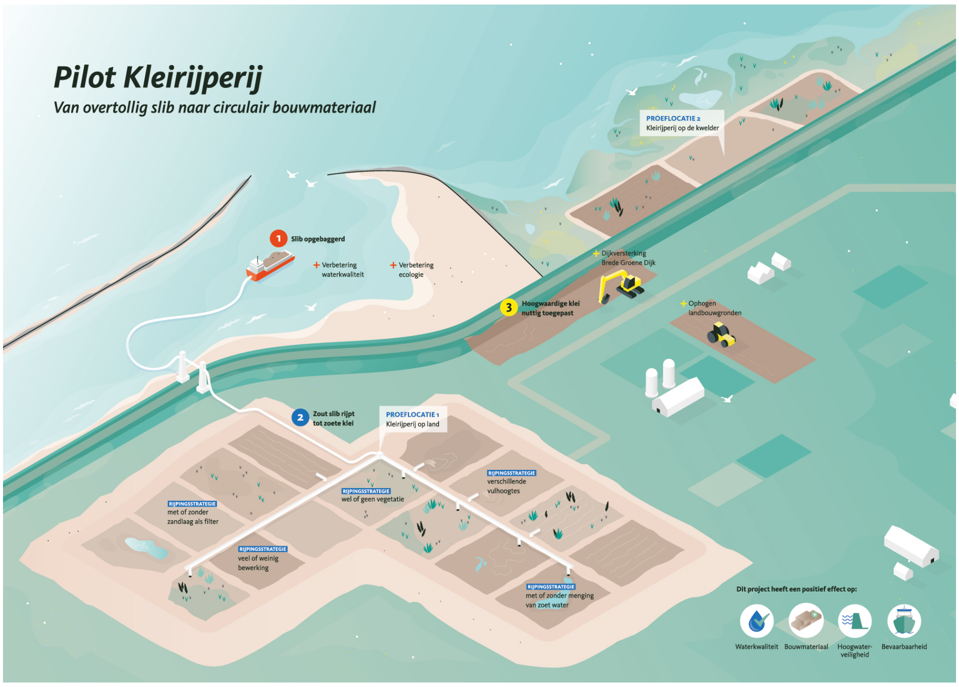

Figure B.1: Overview *Pilot Kleirijperij* (EcoShape, 2020)

the requirements and needs to be considered in each specific project, but the material is still a potential resource for construction.

Road base/pavements

Dredged material is a beneficial resource to use in road construction and pavement. It is an interesting option to reuse contaminated sediments in a beneficial way. For pavements tiles can be created from dredged material. An example of this is the tile form the *Waterweg*. *Waterweg* is a start-up in Rotterdam creating water passing tiles and other products from dredged material (Waterweg).

In the Port of Dunkrik contaminated sediment is reused in road structures. The project is monitored accurately to meet the requirements of the French standard dimension criteria for roads constructed with the usual road materials and see the environmental effects. The material was treated with bio remediation to reduce the organic pollutants level and heavy metals. Some problems were solved with the use of an hydraulic binder and now the road meets the environmental requirements (CEDA, 2020).

Topsoil for agricultural use

As land subsidence is a frequent occurring problem dredged material can be used to elevated agricultural land. The dredged material can contain substances for a fertile soil beneficial for agriculture. A good identification of all the properties and substances in the dredged materials is important as pollution is not desired in agricultural grounds. The material still has potential for this reuse method for direct use or after treatment.

This appendix shows the potential to make the dredging process a completely circular process. Dredged material can be reused and recycled in different ways creating the potential to find a reuse or recycle method for each dredging project.

C

Cost estimation proposed strategies

In this appendix the cost estimation of the case study are further described. In the first section the general cost are summarized and in the second section the cost per proposed strategy are described in more detail.

C.1. General cost

General components determining the cost of the sediment management strategies are more or less the same for every port project. The most important parameters influencing the cost are summarized in Table C.1 below:

cost parameter	cost
mobilisation and demobilisation of the dredge	$ 2,000,000
dredging unit cost	$ 5.00 per m^3
mobilisation and demobilisation for construction	$ 250,000
breakwater unit cost	$ 95.00 per m^3
maintenance cost	0.5% of investment cost
discount rate	4%

Table C.1: General parameters determining the overall cost of the sediment management strategies.

Parameters DOP dredge

Investment cost	
Investment in dredging equipment	$2,500,000 - $4,000,000
Investment in discharge pipeline	$1,000,000 - $2,500,000
Operational cost	
Maintenance of dredging equipment	0.5% investment cost
Regular maintenance dredging	fuel consumption: 160 l/hr and staff
Dredging cost per m^3	$2.50
Dredging location	accumulation locations, near breakwater and leeside breakwater
Dredging frequency	every year, yearly amount

Table C.2: Cost parameters DOP dredge (Arcadis, 2016)

C.2. Cost of the proposed strategies

Strategy 1a - Sediment trap

Investment cost - CAPEX	
Dredging of spit and the sediment trap	
Mobilisation & demobilisation Dredging cost per m^3 Volume to dredge	\$2,000,000 \$5 1,200,000 m^3 + 360,000 m^3
Investment dredging equipment	
Dredging vessel - DOP Discharge pipeline Dredging cost per m^3	\$2,500,000 - \$3,500,000 \$1,000,000 - \$2,500,000 \$2.50
Total cost	\$12,750,000
Operational cost - OPEX	
Regular maintenance dredging	
Dredging cost per m^3 Dredging location Dredging frequency	\$2.50 in the trap around breakwater head every year
Total cost	\$467,500 per year

Table C.3: Cost overview strategy 1a

Strategy 1b - Sediment trap

Investment cost - CAPEX	
Dredging of the sediment trap	
Mobilisation & demobilisation Dredging cost per m^3 Volume to dredge	\$2,000,000 \$5 1,200,000 m^3 + 360,000 m^3
Total cost	\$ 9,800,000
Operational cost - OPEX	
Regular maintenance dredging	
Mobilisation & demobilisation Dredging cost per m^3 Dredging location Dredging frequency	\$2,000,000 \$5 in the trap around breakwater head every 2 years, 2 times amount
Total cost	\$3,800,000 per dredging campaign

Table C.4: Cost overview strategy 1b

Strategy 2 - Sediment bypass system

The initial investment cost of sediment bypass systems vary a lot. From examples can be obtained that the cost can vary between \$7,000,000 - \$20,000,000, Boswood and Murray (1997), Dengate (2011), Keshtpoor et al. (2013), and Tweed Sand Bypassing (2020). The cost depend on the system size, requirements and capacity. For this project a single suction head is proposed with a pipeline discharge system. The total cost is estimate to be around \$11,000,000.

Investment cost - CAPEX	
Construction of the system	
System cost Pipeline cost	\$7,000,000 \$2,000,000
Total cost	\$9,250,000
Dredging of spit and sediment bypass system location	
Mobilisation & demobilisation Dredging cost per m^3 Volume to dredge	\$2.000.000 \$5 1,200,000 m^3
Total cost	\$8,000,000
Operational cost - OPEX	
System operations	
System maintenance System operations Dredging cost per m^3 Pumping capacity	2% of investment cost 10% of investment cost \$1 up to 350.000 $m^3/year$
Total cost	1,125,000 per year

Table C.5: Cost overview strategy 2

Strategy 3a - Blocking structure

Investment cost - CAPEX	
Construction of the groynes	
Construction Volume material groynes	two 120 m long groynes 400,000 m^3 (figure C.1)
Total cost	\$4,050,000
Dredging of spit and shore near blocking structure - first campaign	
Mobilisation & demobilisation Dredging cost per m^3 Volume to dredge	\$2,000,000 \$5 1,200,000 m^3 + 180,000 m^3
Total cost	\$8,900,000
Investment dredging equipment	
Dredging vessel - DOP Discharge pipeline Dredging cost per m^3	\$2,500,000 - \$3,500,000 \$1,000,000 - \$2,500,000 \$2.50
Total cost	\$3,500,000
Operational cost - OPEX	
Regular maintenance dredging	
Dredging cost per m^3 Dredging location Dredging frequency	\$2.50 buffer near the groyne every 1-1.5 years, 1.5-2 times amount
Total cost	\$557,500 per year

Table C.6: Cost overview strategy 3a

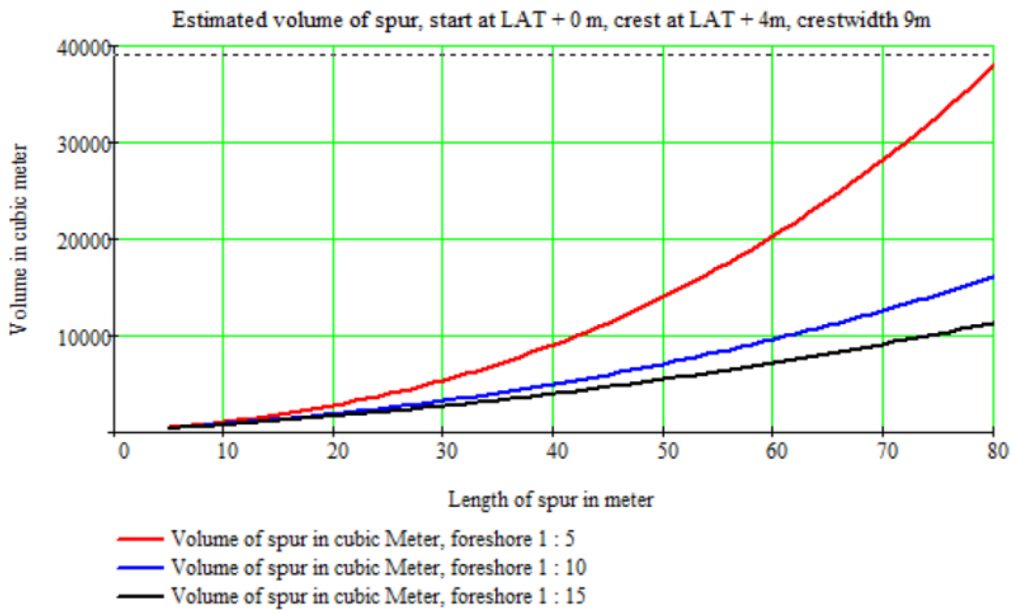

Figure C.1: Preliminary estimate of required volume of spur for various lengths of the spur and slopes of the foreshore (Arcadis, 2016)

Strategy 3b - Blocking structure

Investment cost	
Construction of the groynes	
Construction Volume material groynes	two 140 m long groynes 500,000 m^3 (figure C.1)
Total cost	$5,000,000
Dredging of spit and shore near blocking structure - first campaign	
Mobilisation & demobilisation Dredging cost per m^3 Volume to dredge	$2,000,000 $5 1,200,000 m^3 + 180,000 m^3
Total cost	$8,900,000
Operational cost	
Regular maintenance dredging	
Mobilisation & demobilisation Dredging cost per m^3 Dredging location Dredging frequency	$2,000,000 $5 buffer near the groyne every 2 years, 2 times amount
Total cost	$3,800,000 per dredging campaign

Table C.7: Cost overview strategy 3b

Strategy 4a - Natural sediment bypass

Investment cost - CAPEX	
Construction of the breakwater	
Material cost per m^3 Volume material breakwater extension	\$95 41,000 m^3
Total cost	\$4,145,000
Dredging of spit and breakwater location	
Mobilisation & demobilisation Dredging cost per m^3 Volume to dredge	\$2,000,000 \$5 1,200,000 m^3
Total cost	\$8,000,000
Investment dredging equipment	
Dredging vessel - DOP Discharge pipeline Dredging cost per m^3	\$2,500,000 - \$3,500,000 \$1,000,000 - \$2,500,000 \$2.50
Total cost	\$3,500,000
Operational cost - OPEX	
Regular maintenance dredging	
Dredging cost per m^3 Dredging location Dredging frequency	\$2.50 channel and near the breakwater every year
Total cost	\$377,500

Table C.8: Cost overview strategy 4a

Strategy 4b - Natural sediment bypass

Investment cost - CAPEX	
Construction of the breakwater	
Material cost per m^3 Volume material breakwater extension	\$95 125,000 m^3
Total cost	\$12,125,000
Dredging of spit and breakwater location	
Mobilisation & demobilisation Dredging cost per m^3 Volume to dredge	\$2,000,000 \$5 1,200,000 m^3
Total cost	\$8,000,000
Operational cost - OPEX	
Regular maintenance dredging	
Mobilisation & demobilisation Dredging cost per m^3 Dredging location Dredging frequency	\$2,000,000 \$5 channel and buffer breakwater every 2 years
Total cost	\$3,620,000 per dredging campaign

Table C.9: Cost overview strategy 4b