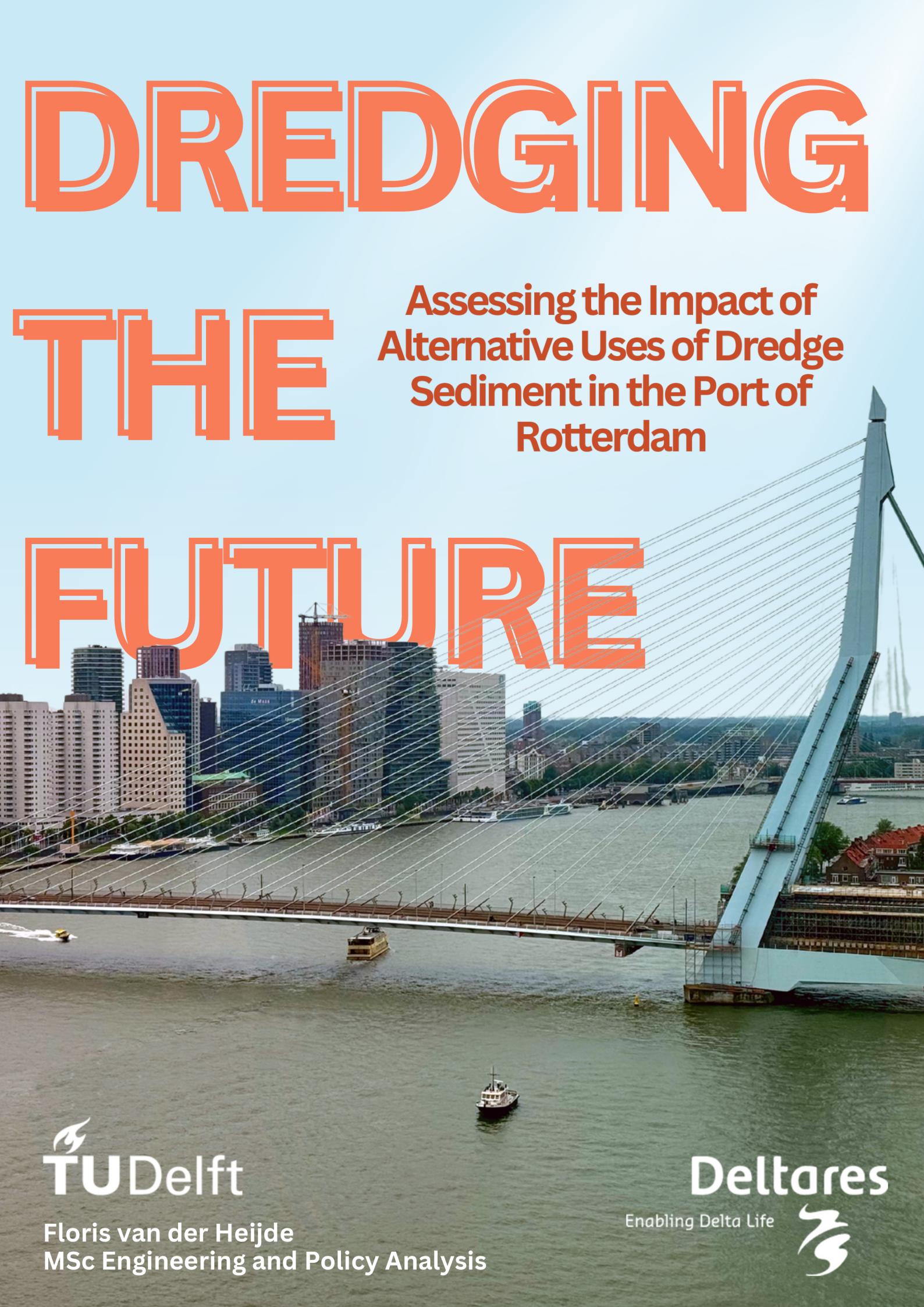


DREDGING

THE

FUTURE

Assessing the Impact of
Alternative Uses of Dredge
Sediment in the Port of
Rotterdam



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Enabling Delta Life



Dredging the Future: Assessing the Impact of Alternative Uses of Dredge Sediment in the Port of Rotterdam

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This research highlights how sustainable dredge sediment reuse can contribute to the UN Sustainable Development Goals: SDGs 9, 11, 12, 13, 14, and 15 (UN, [2015](#)).



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Executive Summary

Background and Motivation

Ports and waterways face a paradoxical challenge: to keep channels navigable, they must continuously dredge vast quantities of sediment, yet most of this material is treated as waste. Across Europe, roughly 200 million cubic meters of sediment are dredged each year, but only about 1% is currently put to beneficial use. The Port of Rotterdam (PoR)—the continent's largest seaport—grapples with this issue on an industrial scale, dredging constantly to maintain safe depths. The conventional solution has been offshore disposal of dredged silts and sands, a practice that is efficient for operations but raises environmental concerns: it generates greenhouse gas emissions (from transport), increases water turbidity, disturbs marine ecosystems, and misses opportunities to recover valuable materials or create new land and habitats. In the Netherlands, initiatives like the PRISMA consortium have begun exploring ways to turn dredged sediment from a waste into a resource, in line with circular economy and sustainability goals. However, realizing this vision at scale requires addressing significant knowledge gaps in logistics, cost-effectiveness, and multi-stakeholder coordination.

Knowledge Gaps. While previous studies have demonstrated technically feasible reuse options for dredged sediment (e.g. using it in land reclamation or as construction material), far less attention has been paid to the practical trade-offs involved in implementing these alternatives at port-industrial scales. To address this gap, this thesis investigates whether a *participatory logistical modelling* approach can support better-informed, collaborative decision-making on beneficial sediment reuse in the Port of Rotterdam. In essence, the research asks: can engaging stakeholders in a quantitative logistics model help identify viable alternatives to dumping sediment at sea, and guide a transition towards more sustainable sediment management?

Research Objective and Questions

The central research question posed is: *Does participatory logistical modelling provide useful insights for facilitating decision-making and collaboration on beneficial sediment re-use applications for the Port of Rotterdam?* In other words, the study seeks to determine if combining stakeholder engagement with logistics simulation can improve understanding of dredged sediment reuse options and aid consensus-building. To answer this question, six sub-questions were formulated, focussing on: Evaluation criteria, alternative implementations and their performance, the effects on stakeholder engagements, and possibilities of future applications.

Methodology

Overall Approach. The research was conducted as a case study under the PRISMA-3 program, combining a thorough literature review, stakeholder engagement, and the development of an open-source logistics simulation model. This mixed-method approach allowed both qualitative insights (stakeholder values, perceived barriers) and quantitative analysis (cost/emission modelling) to inform the evaluation of sediment reuse strategies.

Literature Review and Case Selection. The study began with an extensive review of global dredged material management practices. A wide range of beneficial use options was catalogued—from creating salt-marshes and artificial islands to building up riverbank habitats (groyne cells), raising land elevation in polders, and incorporating dredged sediment into construction materials. From this long list, three representative strategies were deemed most relevant and promising for Rotterdam's context:

- **Base Case — Offshore Placement:** Continuation of the status quo method, where dredged sediment is transported by hopper barges and deposited at a designated offshore dumping site in the North Sea. This option provides a baseline for performance (as it is the current practice).

- **Land Raising — Onshore Placement:** Pumping and placing dredged sediment onto low-lying land (a polder) to raise elevation, potentially creating new usable land or enhancing existing land (for agriculture or nature development) once the sediment dries. This strategy embodies a circular, landscape-based reuse.
- **Concrete:** Processing dredged sediment to serve as a raw material in concrete, effectively replacing a portion of traditional cement or sand in construction products. This strategy ties sediment management to the construction sector, aiming to reduce the need for mined materials and cut cement-related CO₂ emissions.

Stakeholder Engagement. Given the multi-actor nature of port decisions, the study engaged a broad range of stakeholders: the Port of Rotterdam Authority, dredging contractors, Rijkswaterstaat (the national water agency), environmental consultants (e.g. Deltares), infrastructure developers, and academic experts. These actors were involved through semi-structured interviews, a survey, and two interactive workshops. In the first phase, stakeholders helped identify key decision criteria that any sediment management option should be evaluated against. Eight criteria emerged from this process, reflecting a balance of technical, environmental, and social considerations: Safety, Costs, Sustainability, Emissions, Nature Values, Time, Environmental Quality, and Bureaucratic difficulty.

Stakeholders then ranked these criteria by importance, a step that revealed some clear preferences: *Safety* and *Cost* were rated as the most critical factors, while *Bureaucratic Difficulty* and *Environmental Quality* were ranked lowest in priority. (Notably, the lower ranking of environmental quality does not imply stakeholders found it unimportant, but rather that other factors like safety must be satisfied first.) These rankings were used to assign weights in a later multi-criteria analysis, ensuring that the evaluation of alternatives reflects the stakeholders' value priorities. In addition to criteria identification, the engagement process gathered qualitative insights—public acceptance issues, regulatory obstacles, and practical enthusiasm or skepticism—which shaped modelling scenarios and interpretation.

Participatory Logistics Modelling. At the heart of the research is a logistical simulation model built to represent the end-to-end process of each sediment management strategy. Developed with an open-source framework (OpenCLSim in Python), the model simulates all major operations: dredging (sediment extraction by dredger vessels), transport (moving sediment via hopper barges over water, and via truck or pipeline on land), and processing (treatment or placement of sediment at its destination, such as drying and curing for the concrete option).

The results of these simulations were fed back into a multi-criteria decision analysis. Each alternative was scored on the eight stakeholder criteria using the model's quantitative outputs where applicable (for cost, time, emissions) and qualitative judgment where needed (for criteria like safety or nature value). The stakeholder-defined weights were applied to these scores to produce an overall ranking of the sediment management strategies.

Key Findings: Comparative Evaluation of Strategies

Offshore disposal remains the most cost- and time-efficient option, with very low costs (€0.32–€0.43/m³) and minimal emissions, making it the benchmark. However, this option offers no resource recovery or co-benefits and simply removes sediment from the system. Its continued dominance largely reflects systemic and regulatory inertia rather than long-term sustainability.

Land raising was evaluated for truck and pipeline transport. Trucking was found infeasible at port scales, requiring tens of thousands of trips per year, resulting in excessive costs, emissions, and road congestion. Pipeline transport, while requiring a high upfront investment (~€4.5 million), showed strong economies of scale: at high volumes (e.g. Maasvlakte), it approaches Base Case unit costs while delivering additional benefits such as flood protection, habitat creation, and land-use opportunities. Its success would hinge on long-term project continuity, institutional support, and public acceptance.

Concrete reuse investigated sediment dewatering (passive, nature-assisted, mechanical). Passive drying is inexpensive but too slow for continuous port operations, while mechanical dewatering is rapid but costly (~€4/m³) and is energy-intensive. Transport logistics are a major cost and emissions driver, meaning facilities must be sited near dredging and end-use locations. Although legally challenging

(dredged sediment is classified as “waste”), stakeholders valued this option highly for its circular economy potential and CO₂ reduction benefits.

Overall, offshore disposal still scores high due to its unmatched efficiency, but pipeline-based land raising emerges as a strong competitor for large-scale, long-term projects and offers significant environmental and social co-benefits. Concrete reuse remains the most innovative but faces high economic and regulatory hurdles. The analysis suggests that while the Base Case persists as the “easy option,” a transition to beneficial reuse strategies would better align with long-term sustainability goals if institutional and policy barriers can be addressed.

Implications for Policy and Practice

This research highlights several key lessons for policymakers, port authorities, and regulators seeking to make dredging more sustainable. First, **evidence-based decision-making** is essential: combining quantitative modelling with stakeholder input allows decisions on infrastructure (e.g. pipelines, dewatering plants) to be grounded in transparent cost–benefit analysis rather than intuition. This supports more robust, defensible investment choices under uncertain futures.

Second, the results underscore that **scale is critical**. Many innovative options (such as pipelines or mechanical dewatering) only become competitive at high, sustained dredging volumes. Long-term planning and potentially regional cooperation between ports may be needed to aggregate sediment flows to achieve economies of scale and justify capital-intensive investments.

Third, **multifunctional land-use integration** can turn dredged sediment from a disposal problem into a climate adaptation resource. Aligning land raising with flood protection, habitat creation, or urban development projects can unlock co-benefits and attract funding, but requires coordination between port, municipal, and regional planners.

Fourth, **regulatory reform** is needed to enable circular economy pathways such as sediment-based concrete. Reclassifying clean dredged material as a resource rather than “waste,” developing certification schemes, and streamlining permitting processes would reduce barriers to innovation. Without such changes, promising reuse strategies may remain trapped at pilot scale.

Finally, **stakeholder engagement** should be institutionalized as part of sediment management planning. Early, participatory modelling fosters transparency, builds trust, and helps identify and address social or logistical concerns before they escalate into opposition. This is crucial for large-scale projects with long time horizons, where public support must be maintained over decades.

Conclusion

This thesis demonstrates that participatory logistical modelling offers a robust framework for evaluating dredged sediment management options. By making trade-offs between cost, emissions, and sustainability explicit, the approach clarifies why **offshore disposal remains dominant**—its low cost and operational simplicity are difficult to beat. Yet this dominance reflects short-term efficiency rather than long-term value: disposal forfeits sediment’s potential as a resource and perpetuates environmental externalities.

The analysis shows that with sufficient scale and infrastructure, **Land Raising via pipeline transport** approaches cost parity with dumping while delivering substantial co-benefits for climate adaptation and biodiversity, making it the most promising alternative. The **Concrete reuse pathway** represents an even more ambitious circular solution but faces steep technical, regulatory, and logistical hurdles that must be addressed through policy innovation and industry uptake.

The findings suggest that port authorities should not view sediment management as a binary choice but as a portfolio problem: combining conventional disposal with strategically targeted reuse projects could balance short-term efficiency with long-term resilience. The participatory modelling framework developed here equips decision-makers with a shared, evidence-based platform to test scenarios, explore trade-offs, and build consensus. As such, it provides both a practical tool for Rotterdam and a transferable approach for other ports aiming to move beyond “business as usual” towards a more sustainable sediment management paradigm.

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Introduction

This chapter contains a brief literature review of relevant background and key concepts to this research. Sources are gathered through google scholar and scopus using broad search terms and iterating based on search results. Some additional sources are gathered through google searches as for example specific reports on pilot projects are not always available through academic search engines. Sources were filtered by titles and abstract to filter for relevant papers.

1.1. Problem Description

Large scale river ports and urbanisation around rivers have disrupted the natural dynamics of rivers. Naturally rivers sediment and erode their banks and in the process slowly move. Rivers can no longer really exhibit this behaviour and as a result sedimentation largely happens on the bottom of the river channel. Unfortunately sedimentation on the river floor leads to the shipping channels losing depth and thus inaccessibility to shipping vessels. As a result in order to keep shipment flowing through ports they have to regularly dredge out the deposited sediment from their shipping channels. This dredge sediment that would have naturally ended up as part of the land or in the sea now has to be moved somewhere. In the Port of Rotterdam(PoR) area the yearly volume of dredge sediment is around $12\,000\,000\text{ m}^3$. The vast majority of this sediment currently gets moved out to sea and has to be placed quite far off shore to avoid the risk of it flowing right back into the port. As such the PoR is exploring alternative methods of sediment handling.

1.2. Background

1.2.1. Current sediment management approaches

Dredge sediment management varies by country, location, type, and contamination level. The main methods are open-water disposal, contained aquatic disposal, and upland disposal. Each method can be further divided into subcategories and different countries or regions can have different classifications. The Port of Rotterdam uses two key methods, the majority of their clean dredge sediment is moved to an open-water disposal site in the North Sea where the sediment is dispersed by the tidal dynamics. The contaminated sediment is relocated to a contained aquatic disposal site called “the Slufter” (Kirichek et al., 2018). The US army corp of engineers outlines extensive options including dispersive and non dispersive unconfined disposal, beneficial use, and several options for contaminated sediment in their Sediment Evaluation Framework for the Pacific Northwest (2016). Notably, this is just for one region of the US and other approaches are in use in different areas. Craney Flat in Portsmouth, Virginia is an example of contained near shore disposal where all the vast majority of sediment dredged for the region is relocated to. Depending on the method used, the relocation point, and dredging location the required transport of sediment material can be significant, and unless many locations are created and large ports will have to transport sediment over significant distances. This transport is quite expansive and emission heavy.

1.2.2. Alternative applications of dredge sediment

Conservation and restoration of Nature

Several approaches exist that aim to restore or support existing natural areas or create new ones as a way of compensating areas that have been destroyed by human intervention. A large scale pilot project which was completed in the Netherlands is the construction of the “Markerwadden”, the “markermeer” is a artificial lake in the Netherlands that started suffering from ecological collapse due to loose sediment blocking sunlight. The “Markerwadden” were created to trap the sediment and create new habitat for birds to live (Irwing, 2023). The project has been successful yet significantly costlier than anticipated and needs consistent maintenance. Smaller projects located in the Port of Rotterdam area also exist, all in active pilot phase. Project “groene poort” used rubble to mostly close of groyne areas and fill them with dredge sediment aiming to create salt marsh like areas for flora and fauna development (Land+Water, 2023). The tidal parks project aims to combine nature development with recreational areas in recreational spaces that experience tidal dynamics due the ports connection with the sea. Internationally similar projects with the aim of creating ecological value with dredge material instead of treating it as waste (Aiken et al., 2022; Rijks et al., 2027; van den Berg et al., 2022). Furthermore, there are also projects exploring the use of other waste materials in conjunction with dredge sediment to strengthen the ecological effects (Foster-Martinez & Variano, 2018). It is important to note that most projects in this category can accommodate a significant amount of sediment but only once, except for some minor upkeep. Furthermore, within the direct proximity of the port there may be limited locations suitable for large scale nature building project. As a result they may not be optimal for the ports desire to long term reuse 1 million cubic meters of sediment yearly but may be used as a bridging project.

Infrastructure

Numerous methods exist for using sediment that fit this category. Depending on the application a significant amount of processing may be required for the sediment to be useable. This processing can require a significant amount of space as 1 million cubic meters can cover a square kilometre with a metre thick layer. Several pilot projects have been completed in recent years when it comes to using dredge sediment for dike reinforcement. The “klijrijperij” essentially dried sediment on a large scale and transformed it into useable ground to use in traditional dyke reinforcement (de Vries et al., 2023). Pilot project “meegroeiendijk” is exploring the possibilities of slowly increasing dikes in height by spraying them with water mixed dredge sediment. Both project show promising results and could be implementable at large scale (van Puijenbroek, n.d.). Alternative methods for small dike construction also exist that use geotextile tubes filled with sediment supported by rock and then seeded with plants. Though this method likely is not very relevant in context of the Port of Rotterdam. Road construction also has promising possibilities, Neo-Eco a French consultancy has successfully completed numerous large scale projects which include the use of dredge sediment as mineral source in asphalt products (van der Heijde, 2024). Furthermore, sediment could be used to even out road bedding assuming it matched the required criteria or mixed with other materials in order to achieve the desired material (van den Berg et al., 2022).

Construction materials

Dredge sediment can be used as a mineral source in all sorts of construction materials. Various studies and pilots have shown potential, though large scale applications remain limited. The sea silt ceramics project is exploring the potential of sediment as source material for the ceramic industry including brick manufacturing (Humade, n.d.). Netics is exploring Port of Rotterdam sediment as source material for concrete analogous materials. Other companies have successfully developed concrete and asphalt materials using dredge sediment as mineral source (van der Heijde, 2024).

Agriculture

Dredge sediment can be used to raise agricultural land and reconstruct the top soil. This is arguably the traditional way to process dredge sediment from rivers and waterways, sediment is placed on the riverside and driven over the land by local farmers during the off season (van der Heijde, 2024). The use of heavy machinery in modern day industrialised farming leads to severe compacting of the top soil and the world wide loss of top soil is ever growing. It is possible to use dredge sediments as agricultural land, however, the composition of the dredge sediment is very important and the potential pollutions a potential problem factor. Without careful implementation crop yields could decrease. Furthermore, the

Port of Rotterdam has large amount of salty sediment which would need desalination before useable. A pilot project is underway that explores the land raising with pumped in watery sediment, this does however occupy the land for 3-5 years (Eems Dollard 2050, 2021). A group exploring the use of lake sediments for agricultural land is exploring the potential for organic material rich sediments to be used as soil enrichment possibly reducing the required fertiliser. So far results have been positive but not conclusive on crop yield increases. Further, large scale experiments were suggested, unclear if they have been carried out (Brigham et al., 2021).

1.3. Knowledge gap

A significant amount of research is ongoing or completed regarding application possibilities of dredge sediment mostly focussed on technical feasibility. Several review studies have also been done on what methods exist to beneficially use dredge sediment (Carreira et al., 2025; Solanki et al., 2023). In fact companies have already formed that offer products made with dredge sediment (Humade, 2023). It seems that the technical feasibility is quite extensively researched and can be achieved if so desired. However, the other side of implementing alternative solutions on a large scale is less extensively researched. Though some research has been done into the impact of stakeholder engagement on decision making processes for dredge sediment management, it is limited to multi-criteria decision analysis (Collier et al., 2014; Clifford-Holmes et al., 2017). An alternative approach which includes logistical modelling has not been done before and could create a relatively accurate representation of possible alternative scenarios including emissions and time based on model simulations.

1.4. Research question

In order to address the knowledge gap research needs to be done in the impact of using logistical models that evaluate different possible alternative solutions as a facilitatory tool in multi-actor decision-making. In this research this will be studied via a case study of the Port of Rotterdam as they are exploring beneficial sediment re-use applications but find progressing through the multi-actor decision making process challenging. As such the research question “Does participatory logistical modelling provide support in a framework for facilitating decision making and collaboration on beneficial sediment re-use applications for the Port of Rotterdam?”

1.4.1. Sub questions

In order to address this question several sub questions are formulated.

1. What stakeholders are relevant in decision-making for the sediment management strategies of the Port of Rotterdam and do they have the capacity to significantly influence decision-making?
2. What are key criteria for the varying stakeholders to decide whether or not to participate in implementing an alternative sediment management approach?
3. How do stakeholders rank the criteria in importance for decision-making?
4. What are the impacts of the alternative sediment management solutions according to logistical modelling?
5. How does a participatory logistical model effect stakeholders understanding of the sediment management problem?
6. What implementations perform best when scoring alternatives according to the stakeholder criteria, based on the model, stakeholder input, and literature?
7. Based on the experiences from the case study, what would a framework with participatory logistical modelling look like for dredge sediment re-use problems?

1.5. Reading guide

This thesis contains 6 chapters including the introduction. The following chapters are Status Quo, Model Setup, Model Results, Analysis and Interpretation, and Discussion and Conclusion.

The Status Quo chapter will through literature study, cover what the existing common methods of dredge processing are, what alternative methods exist, how the stakeholders feel about alternatives, what the

Port of Rotterdam area is like, and how dredging and processing methods work.

The Model Setup chapter will cover the specifics of how the model simulates the dredging operations and consecutively the processing implementations.

The Model Results sections will explore all the results produced by the model and an initial interpretation. This includes numerical comparison of the cost, emissions, and time impacts of all applications under scrutiny.

Analysis and interpretation combines the model results with more subjective judgements on the other decision-making criteria to form an overall picture of how the applications compare. Stakeholders inputs and considerations also get included and evaluated in this chapter.

Finally, Discussion and Conclusion, discusses the results, their potential impact, the limitations, and possible future work. Finally, it concludes with answers to all research questions and final recommendations.

Methodology + Case Description

2.1. Research Methodology

In order to address the research questions a mixed methods approach is selected to collect input from stakeholders and combined that with logistical modelling methods to create see how stakeholders interact within the decision-making sphere.

2.2. Case Study

The research is performed as part of an internship at Deltares, as part of a larger project of the PRISMA-3¹ consortium. The PRISMA-3 project is divided into several work packages, and this research falls under "Work Package 3: Beneficial reuse of dredged sediment on a large scale". As researcher connected to the consortium PoR was very accessible and as they had significant interest in potential results from the research this meant it was straightforward to make this research a case study specifically for the Port of Rotterdam.

A case study is of interest as it makes doing analysis of complex implementation projects far more tangible, allowing the use of significantly more accurate inputs for modelling. Furthermore, exploring possible implementations with directly involved stakeholders allows findings grounded in context of the case rather than somewhat generic broadly applicable findings as would come from limited desk research. By bridging the gap between academia and industry this allows the results to be more directly implementable by the industry partners in the consortium rather than requiring a complete new analysis based on outlines developed in desk research. Finally, a case study allows getting insightful views in how stakeholders interact with the other methods explored in this research and thus whether further exploration and research could be of interest.

2.2.1. Literature Study

In order to establish an understanding of how the current operations are and what alternative methods exist a literature study is the start. Furthermore, this will also provide a better insight in the relevant stakeholders and how they relate to the possible projects. This required several different search methods and terms. Sources for stakeholders and relevant projects a normal search engine is used with search terms of the relevant stakeholder, usually a business name². For scientific research on dredging operation or alternative implementations of sediment scientific research data bases were used with search terms combining "Dredge sediment", "implementation", "concrete", "construction materials", "logistical simulation", and "decision-making".

¹Programma Innovatief Sediment Management voor Havens, english: Programme Innovative Sediment Management for Ports

²existing knowledge of researcher

2.2.2. Stakeholder Input

Stakeholder input is very important when doing a case study as it provides an view on how the actors actively engaged with the subject material actually think about the current situation and any potential alternatives. As the project was done within the context of the PRISMA-3 consortium this allows for the use of existing consortium meetings, where workpackages provide updates on the research, to be used for data collection. The methods of collection of stakeholder input involve both an anonymous survey and anonymous notes collected during open discussion by stakeholders on directed topics.

Engagement

Stakeholder engagement has been shown to effectively facilitate decision making processes in complex problem settings with many stakeholders. By involving stakeholders actively in a model building process stakeholders can feel more represented in the conclusion of the outcome and as such be more supportive of the result (Clifford-Holmes et al., 2017). When it comes to stakeholder engagement in dredge sediment management some research has been done that increased stakeholder engagement can facilitate decision making. This research focussed on a multi-criteria decision analysis weighing varying options including beneficial use and innovative technologies. One of the conclusions was that participatory model building led to a shared understanding of the dredging issues, and as such facilitated decision making (Collier et al., 2014). Other existing research in stakeholders in dredge sediment decision-making processes tends to focus on either the communication of information to stakeholders (Cutroneo et al., 2014), or the necessity and associated risks of involving stakeholders (L Gerrits, 2004). This research will specifically further explore stakeholder involvement in modelling, and the impact of logistical models, on stakeholder decision making.

2.2.3. Logistical Modelling

Logistical modelling of dredging operations is not very new, in order to employ available resources as efficiently as possible modelling has been used for quite a while (Blasland, Bouck & Lee Inc., 2006). More recently van Oord together with TU Delft developed an open source python package to facilitate the logistical modelling of dredging operations (de Boer et al., 2022). Generally, these logistical models are used for optimisation of costs and resources not complex decision-making processes. As defined by Voinov et al. (2018) Participatory Modelling is “a purposeful learning process for action that engages the implicit and explicit knowledge of stakeholders to create formalized and shared representations of reality”. This can include models constructed in work sessions with stakeholders to actively include them in the modelling stage. However, it can also refer to the use of models constructed by a researcher to align stakeholders views without them actively partaking in the modelling stages. Participatory logistical modelling is the use of logistical models in a participatory setting or approach. This is a growing domain though the extend to which logistical simulation is used is still somewhat limited (Singh et al., 2021). Applications to dredging processes and supply chain seem as so far to not exist. As such this research will be exploring exactly that section, and how the modelling can assist the decision making process.

2.3. Case Description

This research was done as a case study provided by the Deltares as part of the PRISMA3 consortium. Within the consortium several workpackages exist and the package this research falls under is “work package 3: Beneficial reuse of dredged sediment on a large scale” (Deltares, 2025). The case exploring the alternative uses of dredge sediment specifically in the Port of Rotterdam area as this is a consortium partner. Previous research identified several methods of alternative sediment use that may be of interest for this region, and this research further explores the actual processes of implementation and the decision-making elements of moving to alternative methods of sediment use.

2.3.1. Port of Rotterdam

The Port of Rotterdam has to dredge a large volume of sediment in order to keep their shipping channels operational. The Port of Rotterdam is the busiest port in Europe moving 435 Mt annually. Volumes this large require exceptionally large vessels that need deep shipping channels to be able to enter. These shipping channels slowly become more shallow due to sediment depositions. In order to ensure the cargo vessels continue to be able to move through the Port, regular dredging operations are required

removing the deposited sediment and placing it elsewhere.

The Port of Rotterdam is frequently used to refer both to the physical region and the business operating and managing of the region. This business is actually called the Port Authority of Rotterdam³. The business is owned by the Municipality of Rotterdam and the Dutch Government, and does significantly more than facilitating the transfer of goods from one method of transport to another. As PoR owns and manages all of the land in the port area, they lease all of this land to the businesses wanting to operate in the area, which accounts for a significant portion of their revenue. The area managed by the port encompasses 105 km² and requires significant infrastructure to keep everything connected. The businesses operating in the area are for a significant portion those focussed on the storage and transferring of bulk cargo and petrochemicals which is largely destined for locations far beyond the port.

PoR requires a lot of construction materials in order to manage all of these business locations. These materials are two of the three major contributors to emissions for the company, the third being dredging operations. The key materials in question are concrete and steel, as recent research shows that using sediments in concrete production can reduce production emissions this is a key interest for the port. Using local materials, potentially reducing transport distance for the sediment, and reducing production emissions would be an ideal case for the port reducing two out of three emission factors in one project.

2.3.2. Dredging

Dredging operations are as explained a key part of keeping the port operational, and as a result one of the largest contributors of emissions for PoR. Dredging operations will be explained more in depth in [chapter 3](#), but a quick introduction is given here. Dredging can be viewed as using a giant vacuum to remove unwanted material from the bottom of a channel or body of water generally. This material has to then be moved somewhere else to be disposed off. The main placement locations are approximately 15 km off-shore. The sediment that is removed in PoR waterways is mostly fine silt sediments from the rivers feeding the delta area and some sands washing in from the sea. Furthermore, dredging vessels used in the area are almost entirely self-contained vessels, meaning they have dredging equipment and storage on board and do the relocating and placing of the sediment themselves. Alternative implementations of sediment would see the sediment be moved to different alternative locations but regardless it has to be removed from the shipping channels and docking locations.

2.3.3. Stakeholders

Dredging operations and sediment relocation projects have several stakeholders depending on how the sediment is implemented. In the traditional case the main stakeholders are PoR, Rijkswaterstaat, and the dredging firms. Depending on how the sediment is processed for alternative use-cases many more stakeholders could become involved or at least interested. If sediment is placed on land the local municipalities, and potentially local inhabitants, as represented by the municipalities, would get a say. Furthermore, research and knowledge institutes are potentially interested in novel applications. Local land owners may also get a significant say in the process especially if their land is the desired application location. If the aim is to use the sediment for material production, manufacturers would likely become involved as it would be preferred to establish a supply chain before starting. Finally, the final clients will have a stake in the requirements, however this could be limited if PoR is the final client. An overview of the potentially relevant stakeholders is shown below, as collected from van der Heijde (2024).

- Problem Owner — Port of Rotterdam
- Dredging operations — Van de Kamp, Boskalis, Deme
- Governmental bodies — Rijkswaterstaat, Municipality of Rotterdam
- Potential industry partners — Netics, Humade, waterweg, blauwe bagger, Struyck, ENCI
- Potential agricultural partners — Local Farmers, Agricultural industry, soil manufacturing
- Research institutions Deltares, Universities, TNO, Rijkswaterstaat, Sovon
- Nature organisation — ARK rewilding, Natuurmonumenten

³Nederlands: Havenbedrijf Rotterdam

- Local land owners — in case land has to be rented for use in an application
- The Public — Local civilians, as represented by local municipalities, related to implementation location and NIMBY situations

As this research project is done under the scope of the PRISMA 3 consortium, several of these stakeholders are already in close collaboration.

3.1. Current sediment applications around the world

As explained, several methods currently exist for managing dredge sediment around the world. There are 4 main methods: Placement at sea, Placement in enclosed wet depots, Placements on enclosed land depots, placement on agricultural land, and land reclamation. PoR uses a combination of both placement at sea for clean sediment and an enclosed pond depot for polluted sediment. Placement on land depots is frequently done in the US together with land reclamation, though often the land can not be used for anything. Placement on agricultural land is often done in Dutch river and canal systems and one of the oldest management techniques.

Dredge sediment can be applied across a wide range of sectors, from ecological restoration to heavy industry. Nature-focused approaches, such as the Netherlands' large-scale "Markerwadden" project and smaller Port of Rotterdam initiatives like "Groene Poort" and tidal parks, demonstrate how sediment can restore habitats, support biodiversity, and enhance recreational spaces. International examples and experiments combining dredge sediment with other waste materials further expand these possibilities. However, these projects often have one-off capacity and are constrained by the scarcity of suitable sites near the port, making them better suited as transitional or complementary measures rather than long-term high-volume solutions.

Infrastructure and industrial applications offer more scalable potential. Pilot projects like "Klijrijperij" and "Meegroei-dijk" show how sediment can be used for dike reinforcement, while other methods include small-scale geotextile tube dikes, road construction materials, and roadbed levelling. Sediment can also serve as a mineral source for construction materials, with initiatives such as the Sea Silt Ceramics project, Netics' concrete analogues, and asphalt products demonstrating technical feasibility. In agriculture, sediment can raise land and improve topsoil, but salinity, contamination, and long occupation times are challenges. Some studies suggest organic-rich sediments could improve soil fertility and reduce fertiliser needs. Additionally, projects have explored combining sediment with other waste streams to strengthen ecological or structural performance, highlighting the versatility of dredge sediment as a resource across environmental, infrastructural, and industrial domains.

3.2. Stakeholder analysis

In order to assess the best possible alternative implementation that could be used to apply sediment in the Port of Rotterdam area, an overview of the criteria is required to rank the solutions. The relevant stakeholders were determined through brainstorming, discussion, and desk research. The relevant stakeholders depend on the application case. Generally PoR and RWS are the key stakeholders who have most of the decision-making power as the problem owner and the regulatory institution responsible for the regulating dredge sediment, water bodies, and land implementations. Many more stakeholders exist when considering alternative implementations as seen in section 2.3.3. Most of these stakeholders however do not have significant power in affecting decision-making. Most important are potential key players, in a case where open land is used for sediment placement or drying this would

be the local land owner and municipality representing the interests of other local inhabitants. In cases where sediment is used for production of alternative materials (concrete) a key player might be local concrete manufacturers as potential partners in developing products. Furthermore, firms specialising in dewatering sediment may be of interest however they would not have significant power and they would be contracted to do work. Finally, the end location of the developed material might affect the stakeholders as localities may have restrictions on what building materials are considered acceptable, this may be minimised if PoR becomes the final client for the materials. All other stakeholders as listed would not have significant power in the decision-making, however, some may still have relevant knowledge or contributions to make especially in pilot projects.

3.2.1. Ranking criteria

Van der Heijde (2024) provides a decent starting ground of relevant criteria for the stakeholders to decide on alternative implementations. To complete the list of criteria further brainstorming with relevant experts created the following list.

- **Time** required to complete the process of the sediment implementation.
- **Costs** incurred by dredging, transport, and processing sediment.
- **Emissions** expelled by dredging, transport, and processing sediment.
- **Safety** of implementation with relation to workers, location, and local inhabitants.
- **Sustainability** in relation to general impact, material reuse, and marketability.
- **Nature Value** referring to value provided to nature that is non human, e.g. coastal ecosystem or land quality.
- **Environmental Quality** referring to human perceived impact on the local environment, including aesthetically, and marketability.
- **Bureaucratic difficulties** relating to the required bureaucratic work required to start applying sediment in a new manner.

In order to be able to score alternative implementations on these criteria in the end it is important to know what weight stakeholders allocate each criteria. To ascertain stakeholders opinions a questionnaire was utilised allowing stakeholders to rank the criteria and introduce new ones they felt might be missing. Current research suggests that stakeholder think that bureaucratic difficulties are the major hurdle alternative implementations face in being implemented.

3.2.2. Scoring alternative implementations

The various alternative implementations under assessment will need to be scored for each criteria. As Cost, Time, and Emissions are more strictly measurable values, they will be scored according to simulation modelling. The other values are scored in deliberation with an expert according to desk research. For each implementation a score of 1-5 will be assigned to each criteria, this score combined with the weights acquired through the stakeholder ranking can then be used to create an overall score for each implementation.

3.3. Implementation selection

In recent years many alternative implementations have appeared for utilising dredge sediment. Van der Heijde (2024) outlines a large number of theoretically possible dredge sediment implementations for the Port of Rotterdam area. As assessing every possible implementation method would not be feasible within the duration of this research a selection is needed of most suitable candidate implementations.

3.3.1. Implementation Locale

The project is focussed on the Port of Rotterdam area and limiting the range of possible locations to within that area reduces the possibilities. Reducing the scope to the Port of Rotterdam area reasonably considers that in further locations local sediment would be preferred as it limits required transportation. The Port of Rotterdam is a highly urbanised and industrialised area severely limiting the possibilities available for large scale implementation. The limited available bare coastline severely reduces the ability to implement large-scale nature-building projects in close proximity to the port.

There are however larger areas of mostly empty agricultural land present in vicinity to the coast-line, thus land-increase projects may be more suitable to evaluate. This land could also be transformed to nature or potentially be urbanised in future to accomodate the growing housing crisis, in which case elevating the land reduces flood risk.

3.3.2. Port business

Port of Rotterdam as a key stakeholder expressed particular interest in concrete manufacturing cases as explored by van der Heijde (2024). Concrete and dredging operations are two of the Port's largest emission factors joined by steel. Steel is given the nature of the port very difficult to reduce. However, anything that could reduce emission factors from both dredging and concrete would be massively desirable. Further exploring the case of concrete makes significant sense as the material could be manufactured and used locally limiting the overall transport involved in the supply chain.

3.3.3. Selected Implementations

In order to assess a variety of implementations that cover a swath of possible end uses, Land Raising and Concrete base material, were selected as the expansive cases. In order to accurately analyse the impact of these alternatives they have to be compared to the Base Case, being the current scenario. As such we get three main implementations which will each have their own specifics as explored in following sections.

3.4. Dredging source

In order to assess the impact of dredge implementations, especially the logistical impacts, we need to know the source location. This allows us to determine the routes, dredging vessels will need to take. Furthermore, we need to be certain that there is enough sediment available to facilitate a yearly usage of $1\,000\,000\text{ m}^3$. Van Veelen et al. (2024) mapped all the dredging operations in the PoR area, with volumes and sediment quality. From these maps we can determine that there are two key areas with particularly clean sediment that also house large volumes. These areas are a stretch of Scheur and the majority of de Maasvlakte. The Scheur area has a total amount of $120\,000\text{ m}^3$ available yearly, and for the Maasvlakte the number is assumed to be around $1\,000\,000\text{ m}^3$ as the number is listed in larger blocks which slightly overlap with not completely clean sediment. The cleanest label for sediment in these parts of the PoR area is "always applicable"¹ within the "Environmental Testing Framework Placing in Fresh Surfacewater"². This is the only sediment considered for the cases in this study as they would be the easiest to utilise, legally and ethically.

3.5. Applications

This section will cover facts and aspects for each of the selected implementation methods. These will generally cover dredging, transport, processing, and placement. This section covers the specifics of each implementation but not the model implementation of each step, that will be in the next section.

3.5.1. Base Case

Firstly, lets look at the Base Case as this is the current scenario and not a hypothetical alternative. The Base Case involves dredging material from all throughout the port and shipping that with the same vessel to a placement location $\pm 15\text{ km}$ off shore.

Dredging

Dredging operations can be performed with a wide variety of vessels with varying operational aspects. For the selected locations, dredging operations can be performed with quite large vessels with large internal volumes, due to the deep and wide shipping channels. There are several main types of dredging vessels: Trailing Suction Hopper Dredgers(TSHDs), Suction Cutter Dredgers(SCDs), and Grabber Dredgers. Only Trailing Suction Hopper Dredgers and Suction Cutter Dredgers can operate efficiently with large volumes. TSHDs are generally more commonly entirely self contained with onboard storage for sediment to operate while moving, whereas SCDs are generally meant for more

¹Dutch: Altijd Toepasbaar

²Dutch: Milieutechnische kwaliteit toetsingskader toepassen in zoet oppervlaktewater

stationary precision work with no onboard storage. Given the needs of the PoR they most commonly implement TSHDs, as they mostly need maintenance dredging of existing shipping channels that don't require high precision. TSHDs are essentially giant vacuums for the sea/river beds, as seen in [Figure 3.1](#), the vessel has a suction arm that trails along the sea floor as the ship moves which pumps up the sediment into the sediment storage. The main dredging operations in the selected areas are as such done by one of these vessels moving around and hoovering up excess sediment. Storage capacity is generally around 4500 m^3 to 8000 m^3 (Royal Boskalis Westminster N.V., [2025](#)) and as such a significant number of trips are required to cover $1\,000\,000 \text{ m}^3$ of sediment.

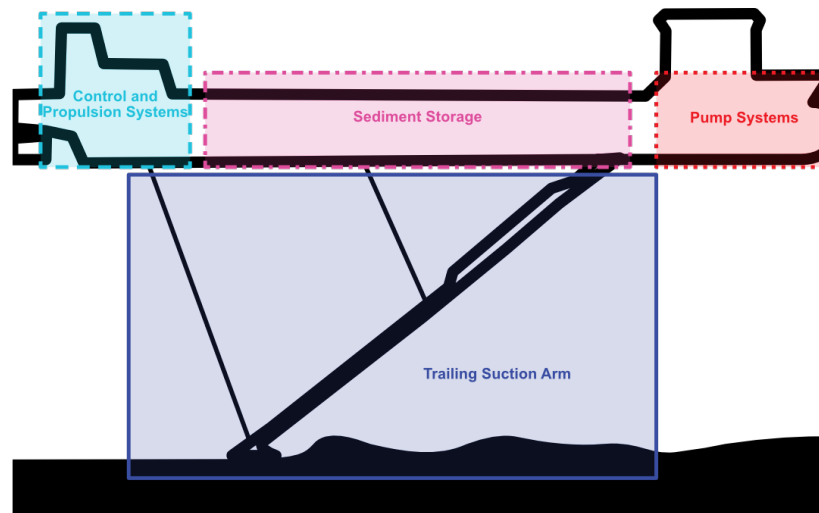


Figure 3.1: Overview sketch of Trailing Suction Hopper Dredger's key components

Transport

When a vessel has hoovered up enough sediment to fill its storage capacity it had to move in order to unload. The placement location is around 15 km off shore. As per Informatiehuis Marien et al. ([2025](#)) there are several designated areas for placing dredge sediment off-shore. Kirichek et al., [2018](#) explains that only two of these are used by Port of Rotterdam for maintenance dredging placement. Using publicly accessible AIS data (NATO Shipping Centre, [2021](#)), it is possible to assess which location vessels dredging in PoR generally use. Records from several different times show that the dredging vessels operating in PoR generally use placement location Verdiepde Loswallen³. As shown by [Figure 3.2a](#) this is the location nearest to PoR and as such would make sense from an efficiency standpoint to use. Between the dredging locations and the placement location ships will generally move as fast as possible and take as direct a route as possible. The routes from the starting locations would look as shown in [Figure 3.2b](#) overlapping for the last stretch taking a direct line to the placement location. In order to verify this vessel transponder data (NATO Shipping Centre, [2021](#)) also known as AIS data can be used to view the highest density locations. As it would be expected that the placement locations would have quite high density it should have an overlapping area if layered with Loswal locations. This is shown in [Figure 3.2c](#) to indeed be the case.

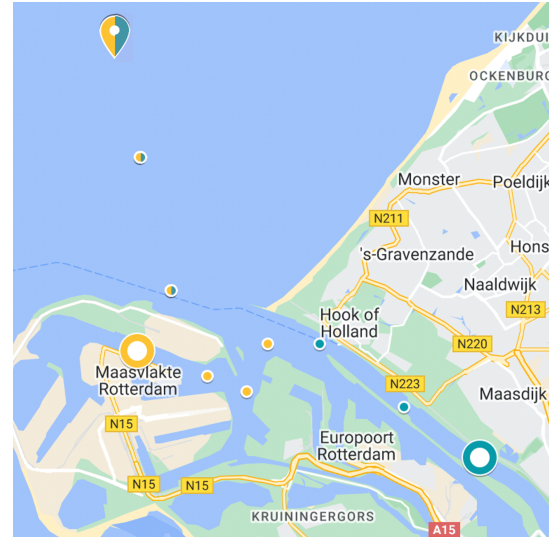
Placement

Dredging vessels generally have any number of three main unloading methods available, varying per vessel design (Royal IHC, [2024](#)). [Figure 3.7](#) shows the methods, Vessels with bottom door unloading ([Figure 3.3a](#)) have big trap doors in the underside of their dredge storage which can open to release all in a very short time. Mounted crane unloading ([Figure 3.3b](#)) is generally found in crane dredging vessels, more commonly used for small-scale operations. Finally, fluid pump unloading ([Figure 3.3c](#)) allows dredging vessels to unload the liquid dredge either by spraying it from the front or, by connecting to a pipeline, straight into an existing pipeline structure. Given that dredging vessels are placing at predefined locations and in quite deep water they would use the bottom door discharge method as it

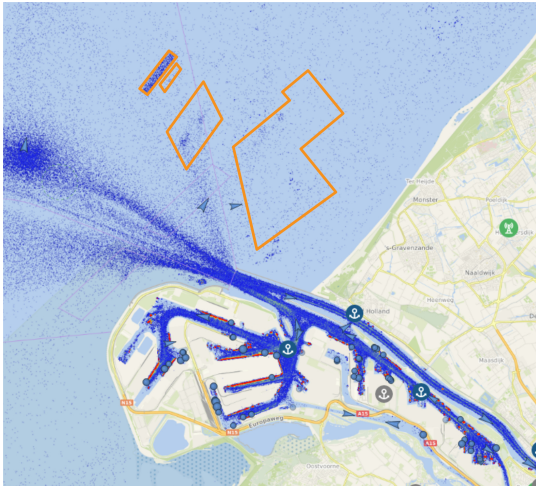
³English: Deepened placement location



(a) Placement locations in the vicinity of PoR (Informatiehuis Marien et al., 2025; Rijkswaterstaat Noordzee, 2013)



(b) Transport routes dredge sediment basecase



(c) Vessel transponder density (VesselFinder, 2025) with the loswal locations overlapped

Figure 3.2: Figures displaying placement locations and routes

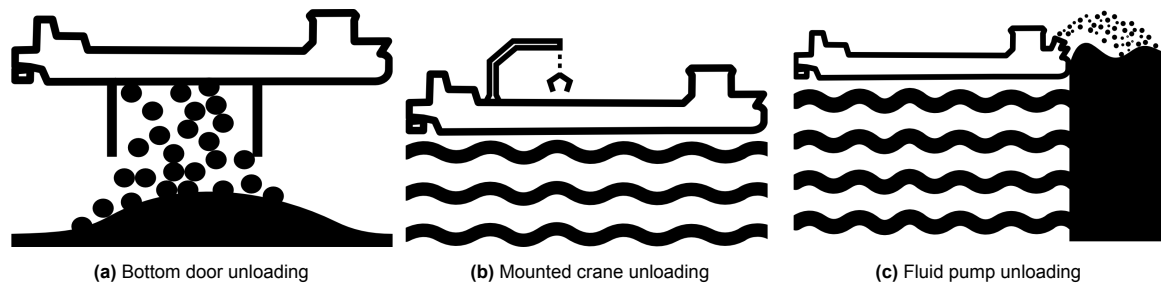


Figure 3.3: Graphics of different unloading methods for dredging vessels

takes the least amount of time and comparatively reduces the amount of pluming and dispersing (Jan De Nul Group, 2025; Royal IHC, 2024).

3.5.2. Land Raising

Land raising will require the selection of the implementation locale in order to discuss the sequential steps of dredging. Dredging will be the same as for the base case as it occurs in the same locations.

Implementation Locale

Land raising and on land drying of sediment both require quite large areas of land in order to suitably accommodate the desired volume to be processed. The selected areas would have to be close to the Port of Rotterdam, ideally the selected high volume dredging locations with clean sediment, in order to make logistical sense. Furthermore, locations further away can only be considered reasonable candidates if they themselves are not near to other high volume dredge locations that would be logistically far simpler to use as a source. Locations should also be relatively close to the waterfront or inland channels suitable for shipping to reduce over-land transport as much as possible. Finally, locations should be generally empty and not protected nature, as such agricultural land is the easiest candidate, as this land could also benefit from potential soil enrichment and compaction reduction.

In order to find suitable locales that meet these criteria, satellite maps were used to identify and rank possible locations. The North side of the port was selected as the primary searching area as the double water way on the South side would lead to significantly longer travel (see route Figure 3.4a) required to access the land. In this search area several zones were selected trying to find large open spaces with no buildings that could accommodate the desired volume. To further narrow down the selection all locations were carefully considered again also for accessibility. The location on the west (see left side Figure 3.4b) would likely be more difficult to facilitate on shore placement due to its existing geography and the presence of the Maeslantkering, a critical part of Dutch flood defense systems. As such the scope was narrowed down to the other two locations (see Figure 3.4c), these also being close to the construction site for a new tunnel which provides docking locations for large vessels. This would be a suitable location to construct pipeline infrastructure limiting the required new construction. Furthermore, these locations are near the high volume clean dredge location along “Scheur” according to the sediment atlas Rijnmond (van Veelen et al., 2024). The purple area was selected for its ability to accommodate larger volumes in thinner layers. Furthermore, both locals have similar accessibility giving the existing infrastructure.

Water Transport

Water transport for the land case is similar to the Base Case as the vessels used will be the same and thus shipping elements will be the same. The only significant difference with the Base Case will be the route taken (see Figure 3.5a), which changes due to the different final location. Notably, in order to accommodate two different land transport methods, two different docking locations are selected. Figure 3.5a shows the route from the Maasvlakte (blue) ending at the truck transfer location and Nieuwe Waterweg (purple) ending at the pipeline transfer location. As a dock was constructed for the construction of the new tunnel, to Rozenburg (see purple marker Figure 3.5b), this could be used to construct pipeline infrastructure along the highway and minimise local impact, and legal hassle. As such the end point for pipeline shipping is selected as that dock. In order to transport the sediment using trucks it has to be moved from the vessels to trucks, in order to make ship usage as efficient as possible the



(a) North side search area(blue) and southern route(yellow)

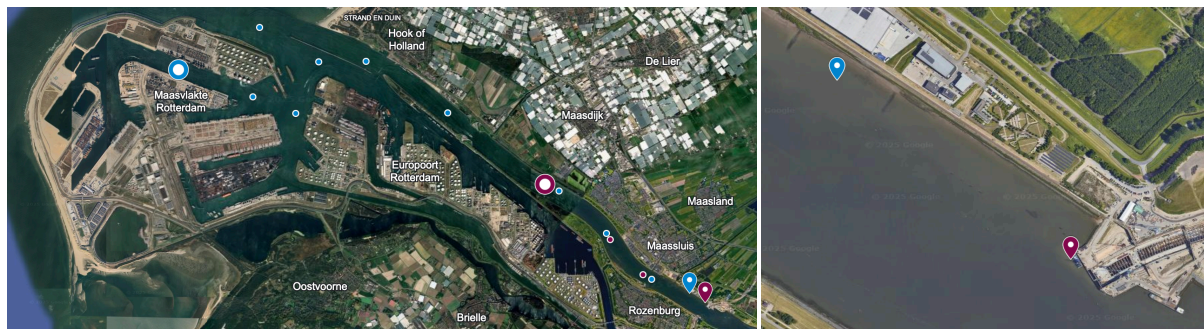


(b) Three possible locations for sediment placement



(c) Final locale showing selected area(purple)

Figure 3.4: Graphics of different unloading methods for dredging vessels



(a) Routes from dredging locations to the unloading locations. Maasvlakte route (blue) stops at the groyne cell. Nieuwe Waterweg route stops at pipeline location. (b) Onshoring locations, showing the groyne cells and dock.

Figure 3.5: Figures displaying placement locations and routes

sediment can be placed in converted "kribvakken"⁴ as temporary storage and then transferred using cranes from land. Groyne cells would be available a few hundred meters from the dock (see blue marker Figure 3.5b).

Land placement

Transferring sediment from the vessel to land would require a different method than the bottom doors, as neither location would be accessible to a vessel. In both cases the vessel would have to use the on board fluid pump (see Figure 3.3c) for the Groyne Cell placement the sediment could be rainbowed in. The sediment can then be picked up from the shore using diggers or cranes. The vessel can also connect the fluid dredge pump directly to a designated pipeline to pump the sediment over a longer distance. This process is significantly slower than bottom door placement. (Royal IHC, 2024)

Land transport

As mentioned several options exist for moving the sediment over the land to the placement location/drying field.

Pipeline

Primarily, a pipeline could be constructed along the new highway construction for the Rozenburg tunnel. This pipeline would mostly run right along the highway meaning there are no serious issues regarding neighbours or private land that has to be crossed, one minor difficulty will be the crossing of the main highway the exit comes off (Figure 3.6). Crossing the highway could be done both over head or underneath. Underneath may be more difficult to execute but make more sense for a long term construction and would allow sediment to flow easier as the curve could be more gradual. Overhead would make more sense for a temporary implementation but might require more pump power as the sediment would have to be pumped up a steeper slope. A pipeline is assumed to have the same throughput capacity as the emptying rate of a TSHD at about 3000 m³ (Royal IHC, 2024; Royal Boskalis Westminster N.V., 2025).

Trucks

The most commonly method of transporting soil materials over ground is trucks. This is not the most efficient method of transport given their limited capacity of about 22 m³ (Biggelaar Groep, 2017). The trucks have the advantage of using existing infrastructure and thus being relatively cheap especially if trucks are already owned by the client. The most efficient route available to trucks is shown in Figure 3.6.

Placement/Drying

Placement at the final location will require spreading in an as even as possible thin layer to facilitate drying. Trucks can achieve this by unloading while moving and, by doing this in a different area every time, spreading out the sediment. A pipeline would if the sediment is liquid enough spread out mostly

⁴the area between two groynes, also known as a groyne cell

by itself. If this were not the case the pipeline would need trucks/diggers to assist with spreading the sediment over the land.

The sediment when drying on land in a lagoon-style construction, generally requires some form of regular agitation or "stirring" to ensure efficient drying (Haliburton & U.S. Army Engineer Waterways Experiment Station, 1978). This can be achieved with diggers or tilling equipment every month or so, allowing the sediment to breathe and evaporate out all the water content. During this process the sediment also releases green house emissions, however as there is no information available regarding the emissions when placing at sea this is left out of the consideration.

3.5.3. Concrete

The concrete process is much the same as the land increase case as in order to use the sediment for concrete production it has to be dewatered first and thus this is assumed to be done at the same location as for the land increase case. However, transport to the drying location is only calculated by truck as there is no reason to analyse that comparison twice. Furthermore, 3 drying methods will be assessed one of which will be done at a different location, which may not be accessible by pipeline.

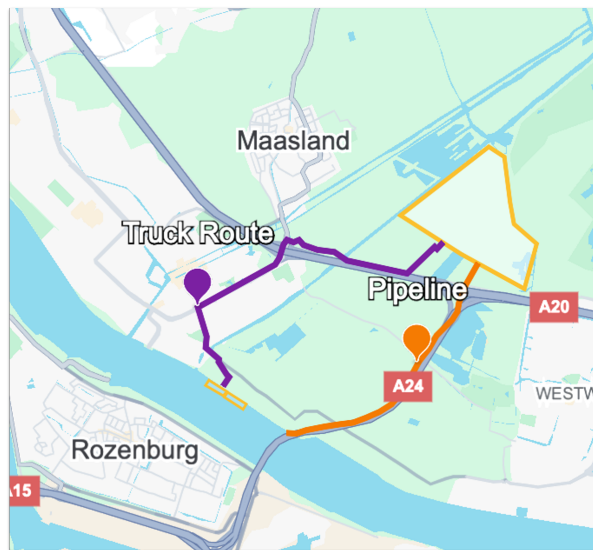


Figure 3.6: Routes of the pipeline implementation and the most direct route trucks could take

Drying

This step is where the difference from the land case becomes apparent. In order to assess the impact of multiple different methods of sediment dewatering/drying three different promising methods are analysed.

Pond

Firstly, the Pond method, which is identical to the land increase case where sediment gets placed into a pond construction. The sediment is occasionally stirred while the water evaporates. This is a rather slow method, actors from the port claim that a 1 m layer can dry within one year, other sources state it generally takes two to three years (Eems Dollard 2050 & EcoShape, 2023).

Nature supported

An alternative to Pond method is nature supported drying, this method uses plants and worms to facilitate dewatering. This promotes aeration and allows the plants to dissipate the moisture as well. Otherwise, this method is essentially identical to the pond method, just reduces the required maintenance and time for drying. Sediment should be dewaterable in about 90 days for a 1 m layer (Medeina Engineering, 2024).

External service

Finally, dewatering of sediment can be done mechanically, this process can be very fast depending on the equipment used. In order to assess the feasibility of this case, a hypothetical company will be created with cost figures. This company will use state of the art dredge dewatering equipment to allow for fast throughput of dredge material. This implementation will be significantly faster processing.

Final destination

In order for the material to be used in a mix to create concrete it will have to be brought to a concrete production location. Logically, given that the port uses a lot of concrete it would make sense to use a local manufacturer. Finding local concrete manufacturers is relatively easy, though importantly we are looking for a location where they process base materials in bulk, and possibly do prefabricated production. It



Figure 3.7: Satellite maps of concrete processing locations

would also be beneficial if the manufacturer is located on the waterfront as doing as much of transport by water would significantly increase transport efficiency. In order to determine what manufacturers locations match these criteria, satellite imagery can be used. Searching for concrete companies in the vicinity of PoR and viewing their locations on satellite imagery two possible candidate can be found. **Figure 3.7a** shows the possible locations (orange/purple) in relation to the onshoring groyne cells (yellow), both locations clearly have the capacity to accept material from offshore. **Figure 3.7c** seems to have a lot of prefab materials on locations, which suggest they manufacture those. **Figure 3.7b** is mostly enclosed so the imagery provides a less clear image of their operations. Notably, Struyk concrete is significantly closer to the drying locations and as such would likely be more suitable transport wise. Furthermore, by reviewing both companies websites it becomes clear that Struyk has a strong emphasis on sustainable concrete development with other base materials (Heidelberg Materials Benelux, 2024; Struyk Verwo Infra, 2024). Given that Struyk already has experience working with alternative materials, this makes them the most logical choice for this hypothetical. Transport from the dewatering location to the processing location could be done by trucks entirely or by trucks and boats together, in which case the trucks would drive to the Groyne cells and then offload onto push barges that go to the Struyk location. Given the added logistical complexity of using multiple transport methods, especially with aligning the differences in transport capacities, the choice was made to go for trucks only for this assessment.

4

Model Setup

4.1. Logistical Simulation

In order to assess all of these cases a simulation model was built to model ship operations, land transport, and drying and processing operations. Figure 4.1 shows an rough overview of the model construction. The model receives input variables, runs the logistical simulation of the dredging vessels, output of that simulation gets used for further processing calculations and Fuel, Cost, and Emission Calculations. All of the combined data gets outputted and saved. The model will be explained step by step. Firstly, input variables, followed by the model, and the processing. Notably, the model also has a lot of model parameters that will be touched upon when relevant.

4.1.1. Input Variables

In order to model any of the suggested cases a number of base inputs are needed for the model to operate. These inputs are defined as: Volume, Application, SecondaryTransport, TertiaryTransport, RoutePath, and Vessel. Volume refers to the total amount of m^3 of sediment that needs to be processed, this is of course dependent on the location that is being dredged from and thus needs to be adjustable. Application is the method of processing, including BaseCase, LandIncrease, and Concrete. Secondary- and TertiaryTransport are the method of transport used to move the sediment over land, they can be None if irrelevant to the application. RoutePath has to provide the model with geographical coordinate data for the model to simulate the ship travels. In order to acquire accurate coordinate data in a simple manner, GoogleMaps' custom map feature was used, this allows the user to put down points, name them, and then extract that data as a CSV file to be used by the model. Finally, Vessel indicates to the model which vessel should be used, and allows it to take the relevant data from the file storing specifications for numerous dredging vessels.

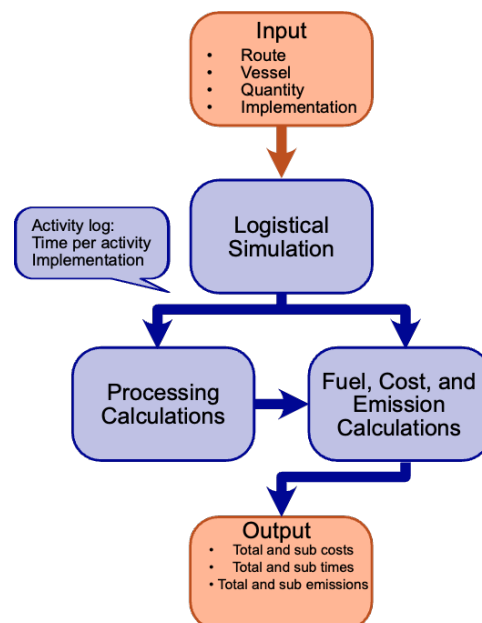


Figure 4.1: Overview of the model code, showing inputs, outputs, and operations

4.1.2. Output Variables

The parameters the model would be providing as output would be Time, Emissions, and Costs. These are the variables that can easily be determined from the model operations. These output variables can be split by every activity in the model leading to separate values for dredging, processing, land transport, and total.

4.1.3. OpenCLSim

In order to process the logistical steps from the dredging in Python a package developed by the TU Delft (dletares? and PoR?)[SOURCE] was used. This Package OpenCLSim allows the creation of vessel entities, that move along coordinate sets and allows for the calculation of operational durations based on input parameters. In order to make the use of this package more straight forward and reduce the amount of coding involved in performing many runs, a bunch of functions were created to automate as much of the process as possible.

Firstly, the simulation environment has to be initialised. After this the classes have to be defined, the package has numerous classes available, the three relevant classes for this simulation are *Site*, *Location* and *TransportProcessingResource*. *Site* and *Location* both are geographical entities, which are used for navigation, and differ in their ability to store resources (read: sediment). *Sites* have a container and can store resources and as such this level can be tracked to track status of the transport process. *Location* is just a navigational point. *TransportProcessingResource* is the class that represents the vessel, it can interact with locations, has speed stats, and can load and unload sediment.

Vessel and Route information has to be loaded next. Route data is extracted from the GoogleMaps exports as mentioned. The CSV containing coordinates is loaded into a dataframe and the entries are transformed to Shapely points that OpenCLSim can understand. After this the Shapely points can be defined as objects from the relevant classes. Using the names defined when creating the map, the function determines whether or not the coordinates should be *Sites* or *Locations*, both the source and destination are defined as objects from the *Site* class, with capacity of the defined volume, and the navigational points are objects from the *Location* class. All these objects are then saved in a dictionary, representing the route. Having defined the route it is time to define the vessel that will be operating the route. First all the vessel stats are loaded into a dataframe including names and operational parameters from publicly accessible datasheets (Royal Boskalis Westminster N.V., 2025). Using the selected ship from the input variables and the dataframe an object is created of the *TransportProcessingResource* with the name and parameters as defined in the data table, and its starting location as the Source(*Site*).

Finally, the activities have to be defined. The activities are essentially what the model is executing and calculating. Main activities are sailing, loading, and unloading. The function defines them as sailing to the *Source* in case the vessel has a different starting location (this would happen in a straight line). Then the vessel will load, which will take $\frac{VesselCapacity}{VesselLoadSpeed}$, after which it will sail along all the navigation *Locations* and at *Destination* it will unload with the $VesselUnloadingSpeed^1$. Having created the activities the simulation can be run and its outputs collected. The simulation repeats all the activities for as long as it takes to fill *Destination*, this represents all sediment having been moved.

The outputs of the simulation are a large dataframe detailing the time it took to complete every *activity* and a Gantt Chart showing the operation. These are the default functions from the package. In order to make the output more usable for further analysis, the dataframe is grouped by *Activity* as the power consumption will generally be consistent per *Activity*. As such per *Activity* the total time spent is available.

Time duration per activity is very useful, and one of the key metrics, however fuel, emission, and costs are also desired as metrics. As such these have to be calculated based on *Activity* duration. In order to be able to store results for every simulation consistently, and not lose too much detail, a table structure was defined to save results in. Table 4.1 shows the subdivision of metrics to calculate and that they are recorded for each *Activity individually*. Fuel consumption is calculated using this equation: $Fuel[L] = Duration[h] * PowerConsumption[kW] * FuelEnergyDensity[L/kWh]$

¹As mentioned this speed differs between land placement and bottom door placement as such vessels can be defined with both a land placement version and a bottom door placement

Table 4.1: table showing the format for results recording

	Time[hours]	Time[days]	Fuel[L]	Emission[kg CO2]	Cost(fuel)[€]	Cost(service)[€]	Cost(crew)[€]	Cost(rental)[€]	Cost(total)[€]
DredgingSailing	0	0	0	0	0	0	0	0	0
DredgingLoading	0	0	0	0	0	0	0	0	0
DredgingUnloading	0	0	0	0	0	0	0	0	0
DredgingTotal	0	0	0	0	0	0	0	0	0
SedimentProcessing	0	0	0	0	0	0	0	0	0
SecondaryTransportMain	0	0	0	0	0	0	0	0	0
SecondaryTransportSupport	0	0	0	0	0	0	0	0	0
SecondaryTransportTotal	0	0	0	0	0	0	0	0	0
TertiaryTransportMain	0	0	0	0	0	0	0	0	0
TertiaryTransportSupport	0	0	0	0	0	0	0	0	0
TertiaryTransportTotal	0	0	0	0	0	0	0	0	0
ProjectTotal	0	0	0	0	0	0	0	0	0

where duration is taken as the total amount of time spent on an *Activity*, PowerConsumption is estimated based of engine powers listed in spec sheets, and FuelEnergyDensity is taken as the standard value for VLSFO². Using the Fuel consumption allows us to calculate the CO2 emissions: $FuelEmissions[kgCO_2] = FuelConsumption[L] \times FuelEmissionFactor[kgCO_2/L]$, again using the known Emission factor for VLSFO. The same can be done for the fuel cost: $Cost(Fuel)[€] = FuelConsumption[L] \times Fuelprice[€/L]$, where the fuel price can be obtained from online sources for local distributors. Finally, crew costs can be estimated using: $Costs(crew)[€] = Duration[months] \times CrewCount \times AverageCrewSalary$, crew counts is estimated at 20² based on similarly sized vessels, and crew salary estimated based on job postings at 3000². All of these calculations are done for each activity and the totals are tallied up and saved into the table as well. The other cost parameters are not relevant for the dredge vessels, however, if another third party were to be contracted, extra costs could be calculated under service costs.

4.1.4. Drying/Processing calculations

The drying and processing values are not really dependent on the transport values and as such can be determined before. Sediment processing will depend on the application.

The BaseCase will have no processing time, costs, or fuel consumption. However, the sediment having been oxygenated through the dredging and placement process will likely release ripening emissions, unfortunately, there is no good data on this process and as such this analysis assumes them to be zero. As this is a comparative analysis, ripening emissions will be emitted from the other cases as well to prevent unwittingly skewing the results. Calculations are added for all implementations, so with good data only the input parameters would need to be changed.

Sediment processing wise, the land increase case and Pond drying for concrete are very similar. Both methods have the sediment placed in a pond style construction and allow the sediment to air dry. In order for the sediment to effectively dry occasional mechanical stirring is required. These stirring operations allow the soil to get aerated and support the ripening process. This is generally done using diggers. Processing time is the amount of time it will take for the soil to dry to the air, current operating assumptions are that a 1 m layer of sediment will dry in one year, as such that is maintained in this model. Furthermore, layer depth and dewatering time are assumed to be quadratically related. As such the drying time is calculated: $DryingTime[years] = (\frac{SedimentVolume[m^3]}{LandArea[m^2]})^2 \times DryingTime1m[years]$. Fuel and Emission are calculated as related to the operations of the diggers for stirring. Fuel requires the amount of stirring requirement: $DryingFuel[L] = DiggerFuelTime[Lh^{-1}] \times DryingTime[years] \times StirringRequirementYearly[h/year]$, emissions are simply calculated with the diesel emission factor, ripening emissions are added but zero as explained for this research. *Fuel costs* are a simple multiplication *diesel cost*. Service costs are taken as the operating time for the digger multiplied by the rental cost including the operator required. Finally, there are the costs for renting the land used for these operations. These costs are based on average hectare costs for the region, multiplied by the time required for the operations. All the costs are once again totalled and all values are stored in the dataframe.

The nature supported case is very similar to the Base Case and the Pond case except the stirring action is performed by worms introduced into the soil. Furthermore, the estimated time for drying 1 m layer of soil is about a quarter of the time as for Pond style dewatering. There is no longer any fuel or fuel based

²Very Low Sulphur Fuel Oil, the most common fuel for dredging vessels

emissions for this case, as no diggers are utilised. The service cost becomes the purchasing cost of the worms: $DryingServiceCost[€] = Volume[m^3] \times WormConcentration[kg/m^3] \times WormPrice[€/kg]$.

The external case is more significantly different as it utilises a completely different method for sediment dewatering. This is a hypothetical company set up using mechanical dewatering equipment capable of high-throughput dewatering. The sediment would be pumped from wet-storage, through a dewatering machine, to dry storage. The processing time would simply be $ProcessingTime[hours] = SedimentVolume[m^3] / ExternalProcessingCapacity[m^3 h^{-1}]$. As the entire facility operates on electricity the emissions are estimated based on the estimated electricity consumption for the dewatering operations. Furthermore, as the operational costs for the facility are entirely combined in the hypothetical set-up of the company they are calculated as the service cost.

Finally, as a possible business case within the Port area, the "Europees Massagoed Overslagbedrijf"³ could hypothetically operate a small version of the external drying facility, as new business case replacing some of the diminishing demands for coal. These calculations will be identical to the external case with different input parameters as the processing capacity would be scaled to the location.

4.1.5. Land transport calculations

Having calculated the parameters for dredging and processing, just Land Transport remains. Two main options are considered for this study, however the model is set up flexibly so it can calculate alternative methods as well.

Trucks

The first of the two main transport options is with trucks. Trucks are frequently used to transport soil materials, however, they do need supporting equipment — cranes or diggers — to load and potentially in unloading. As such the outputs for secondary and tertiary transport are split over *Main* and *Support*. *Main* covers the costs, emissions, and time of the trucks themselves, while *Supporting* covers any and all supporting operations.

Secondary Transportation in the model can be done for any case, in this research it relevant in the Land Increase case as it is taking the sediment to its final destination from the vessels. The concrete case also utilises Secondary transport to move the sediment to the drying location, from there tertiary transport moves the sediment to its final destination. To calculate the Time for truck transport first the amount of trips has to be calculated and then multiplied by the average duration of a trip: $SecondaryTransportTime[hours] = \frac{SedimentVolume[m^3]}{TruckCapacity[m^3/car]} \times \frac{TransportDistance[km]}{TruckSpeed[km h^{-1}]}$. The input parameters for Fuel calculations for trucks are per volume and already consider the amount of trips, as such: $SecondaryTransportFuel[l] = SedimentVolume[m^3] \times TrucksFuel[L m^{-3} km^{-1}] \times TransportDistance[km]$. Emissions are calculated based on a simple multiplication with time and an emission factor for trucks. Costs are simply calculated based on public fuel costs. The rental costs are estimated including operators and thus $ServiceCosts[€] = SecondaryTransportTime[h] \times TrucksRentalCost[€/h^{-1}]$. In order to facilitate transference of the sediment from the groyne cells to the trucks, diggers are assumed to be used. Diggers are assumed to have a certain loading capacity which is used to calculate how long it would take to load all the sediment into trucks. The unloading of the trucks is also calculated, under the support set, however, it is assumed that this is done by the trucks while driving slowly, through tilt containers. Fuel, emissions, and costs are all calculated the same as for the other vehicles. the Secondary Main and Support Transport outputs are then totalled and both the sub values and totals are stored in the dataframe.

All of these operations are potentially also done for the tertiary transport, once the material has dried. The most notable difference for the tertiary calculations is that the volume of sediment concerned is significantly less due to the moisture reduction. Otherwise, the calculations happen very much the same way.

Pipeline

The second main method under evaluation is a Pipeline, capable of pumping liquid sediment. The Pipeline has to be constructed and costs and emissions for this process have to be taken into account.

³English: European Bulk cargo Transference company

Estimations for these impacts are taken into account as the supporting values for this transport method. The estimates are done as a length dependant value, and as such multiplied by the length of the required pipeline. Otherwise, the operation of the pipeline is all calculated under the Main values. It is assumed that — as the pipeline is considered as connecting to the vessel directly — the pipeline pumps sediment at the same rate as the vessel. Furthermore, that a secondary pump included in the pipeline, to support the vessel pump, would be of the same power as the vessel pump. As such $PipelineFuel[l] = (\frac{PipelinePumpPower[kW]}{DieselEfficiency}) / DieselPower[kW \cdot h \cdot L^{-1}] \times UnloadingTime[h]$ where the assumption is that the pipeline is powered by diesel generators. Emissions and fuel costs are once again simple multiplications with factors. Service Costs covers general upkeep costs for the pipeline but not crew or fuel operating costs. Service costs are estimated for the project duration and for the length of the pipeline. Finally, it is assumed that some crew may be required to ensure smooth operation of the pipeline, this is again estimated and calculated for the operation of the pipeline.

Pipelines are best at transporting liquids of liquid sludge materials, as such a pipeline is not considered a viable alternative for the transport of the dewatered sediment, and thus only for the secondary transport outputs.

Alternatives

For flexibility of the model, some alternative methods of sediment transport are accounted for. For example, if a placement location is directly adjacent a accessible waterway, push barges could be used to efficiently transport large volumes of sediment. The model is set up to calculate alternative methods of transport that were not directly considered — due to scope limitations, and selected locations — but could be of interest.

5

Model Results

5.1. Experimental Setup

Having the model setup in order to be able to compute each implementation, specific runs have to be specified to be run for analysis. After completing all these runs, the results then also have to be analysed.

5.1.1. Model runs and parameters

All implementations are run for the full capacity of both dredging locations. However, as the two locations have different total volumes of sediment available a base line is needed to compare. This baseline is defined as $10\,000\text{ m}^3$ of sediment from either location. In order to reduce the amount of runs and streamline the process, this comparison run was run for every variation of the the Nieuwe Waterweg location but only for one of every Maasvlakte implementation. The total run overview can be seen in [Table 5.1](#), where all methods refers to the complete list of implementations: "Basecase, Land Increase Trucks, Land Increase Pipeline, Concrete Pond, Concrete Nature, Concrete External. In order to compare the two open air drying methods — Pond drying and Nature supported drying — some extra runs are done for different layer depths (Highlighted in orange in [Table 5.1](#)). These runs, are done assuming a $200\,000\text{ m}^2$ plot of land and the source being Maasvlakte (not relevant as only used for considering the drying stage). Finally, in order to get a more specific analysis of the benefits of scale in the Land Increase case runs are done for larger volumes — covering multi-year totals (Highlighted in light blue in [Table 5.1](#)

5.1.2. Results

Results of the modelling are combined in a large Excel sheet, initial analysis is done per method, comparing the different dredging locals and volumes. In order to get more comparable values — costs, emissions, and time — they are divided by the amount of cubic meters processed. The per cubic meter values for each case are then ranked and scored to get an overall scoring.

Secondary analysis is performed to provide a clear picture of the relation between layer thickness of drying sediment, and time required to complete dewatering. Furthermore, in order to get clear

Table 5.1: Overview of Model runs by volume per dredging location and implementation combination. [orange text are additional runs for passive drying analysis, blue text are additional runs for benefits of scale analysis.]

	Nieuwe Waterweg (130k yearly)	Maasvlakte (1M yearly)
BaseCase	10k, 130k	10k, 1M
Land Trucks	10k, 130k, 1M, 2.5M, 10M	10k, 66k, 100k, 130k, 200k, 300k, 400k, 1M, 2.5M, 10M
Land Pipeline	10k, 130k, 1M, 2.5M, 10M	10k, 130k, 1M, 2.5M, 10M
Concrete Pond	10k, 130k	10k, 1M
Concrete Nature	10k, 130k	1M
Concrete External	10k, 130k	1M

impressions of scale benefits additional analysis of the land increase case was performed.

5.2. Model inputs and outputs

The model runs require a number of input variable defined for every run. These variables are generally consistent per implementation besides the Volume as shown in [Table 5.1](#). [Table 5.2](#) shows the inputs used for each model run of each implementation. Volume, self explanatorily, tells the model how much sediment has to be moved, similarly Application refers to the application method, Secondary- and TertiaryTransport tell the model what mode of transport is used for the land sections of the sediment transport, RoutePath links to the file containing the route information for the dredging operations, finally, Vessel tells the model which dredging vessel to load. As all implementations, besides the BaseCase, require the sediment to be pumped from the hold they use the StrandwayLand whose inputs are adjusted for pumped offloading, rather than bottomdoor unloading. All other inputs the model uses are consistent per run and can be found in [Appendix B](#).

As covered in [chapter 4](#) the outputs of the model are tables as seen in [Table 4.1](#) furthermore, the model creates a Gantt chart of the dredging operations, and a map output showing the dredging route. The following sections will explore the results per case and the additional analysis steps.

Table 5.2: Overview of input variables off the model runs per Implementation

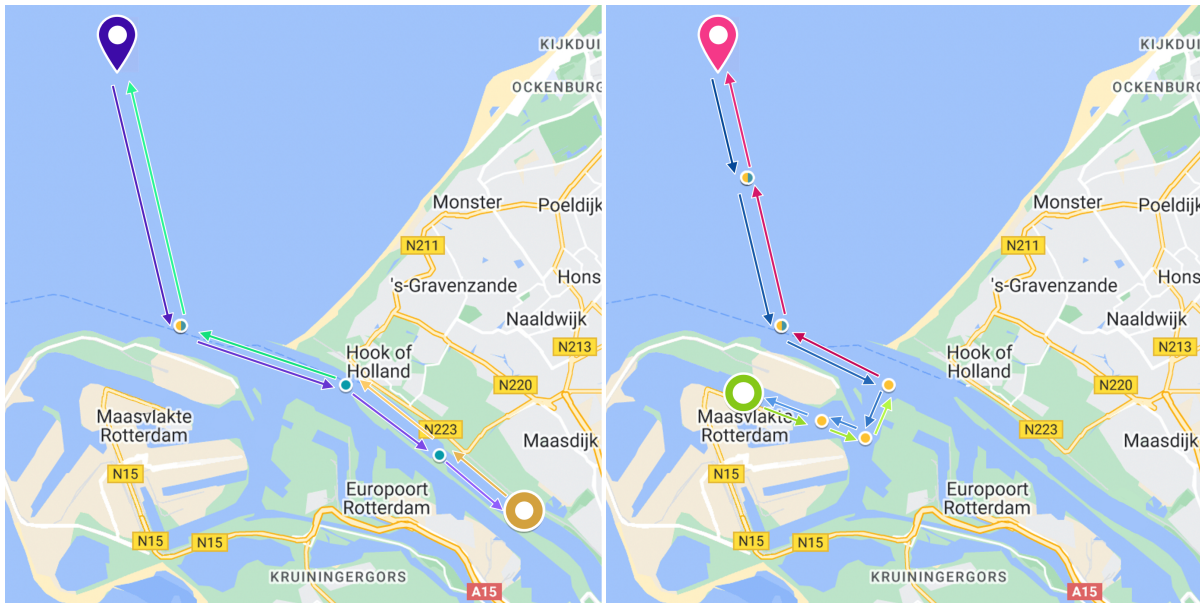
Implementation	Volume	Application	SecondaryTransport	TertiaryTransport	RoutePath	Vessel
BaseCase	Varies	BaseCase	None	None	Varies	Strandway
LandTrucks	Varies	LandRaise	Trucks	None	Varies	StrandwayLand
LandPipeline	Varies	LandRaise	Pipeline	None	Varies	StrandwayLand
ConcretePond	Varies	ConcretePond	Trucks	Trucks	Varies	StrandwayLand
ConcreteNature	Varies	ConcreteNature	Trucks	Trucks	Varies	StrandwayLand
ConcreteExternal	Varies	ConcreteExtrenal	Trucks	Trucks	Varies	StrandwayLand

5.3. Base Case

In order to perform a comparative analysis of the alternative cases, it is important to first understand the Base Case and its impacts. The BaseCase is off shore placement of dredge sediment at pre-specified locations. These placement operations are not considered to be harmful at this locations, and generally considered to be beneficial to the coastal area at large. The simulations limit the placement location to a single possibility that was observed to be the main location used and also mentioned by experts. Both dredging locations — Nieuwe Waterweg and Maasvlakte — have simulation runs for 10 000 m³ and the full capacity of the locations — 130 000 m³ and 1 000 000 m³ respectively.

As the BaseCase only includes dredging operations, and there is no data from the sediment emissions for placement at sea, the output of the model is limited to the Gantt Charts and time, emission, and cost data for the dredging operations. [Figure 5.1a](#) shows the dredging route for Nieuwe Waterweg where the larger annulus indicates the dredging location, the smaller circles the waypoints, and the location marker the placement location. The arrows on the map match in colour to the activities shown in the Gantt Chart — of one dredging cycle— in [Figure 5.1c](#). [Figure 5.1b](#) and [Figure 5.1d](#) show the same for the Maasvlakte dredging location. The Gantt Charts show that dredging cycles for both locations take approximately 3 hours, with the Maasvlakte process being slightly quicker, due to the route being slightly shorter.

The numerical outputs of the model, namely the Time, Costs, and Emissions can be seen summerised in [Table 5.3](#). Notably, the per cubic meter costs and emissions are higher for the lower volumes. This can be explained by the fact that the dredging vessel has a hold capacity of 4500 m³, which means that to transport 10 000 m³ three trips are needed of which the third will be less than a third of capacity. A third of the trips being very inefficient lead to skewing of the results. Furthermore, as the Massvlakte route is a little shorter it is apparent that the costs and emissions are slightly lower for the Maasvlakte route. Overall, it becomes clear that, regardless of which location is used, the BaseCase is quite efficient and affordable. However, this is not unexpected as this is the main method of sediment processing.

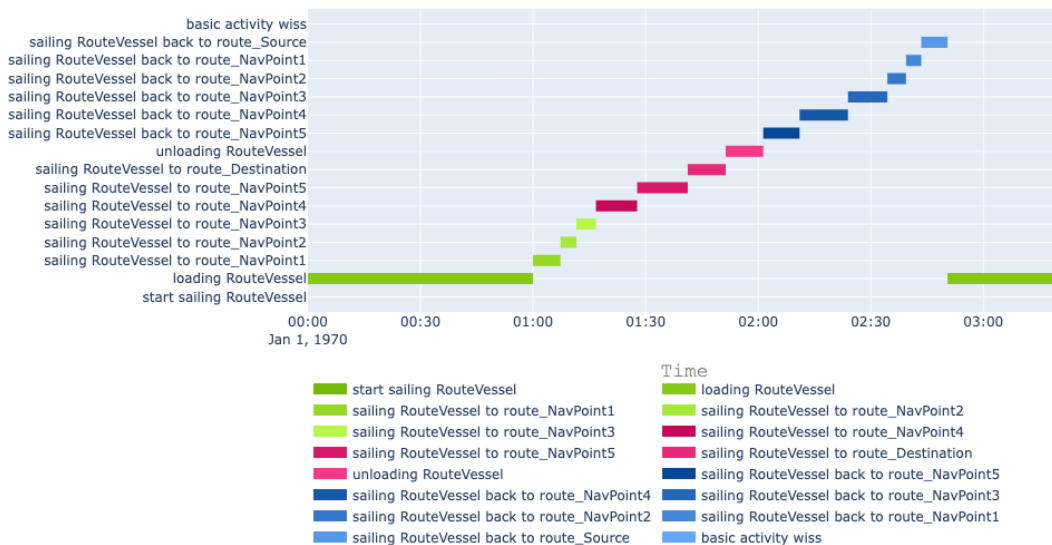


(a) Dredging route BaseCase Nieuwe Waterweg

(b) Dredging route BaseCase Maasvlakte



(c) Gantt Chart showing one cycle the dredging operations for the BaseCase Nieuwe Waterweg



(d) Gantt Chart showing one cycle the dredging operations for the BaseCase Maasvlakte

Figure 5.1: Maps and Gantt charts of the BaseCase dredgin operations with colours matched per activity

Table 5.3: Results model runs BaseCase

	Nieuwe Waterweg		Maasvlakte	
Volume	10k	130k(full capacity)	10k	1M(full capacity)
Total Time [h]	9.2	89.3	8.9	665
Total Costs[€]	4,287.00	41,218.00	4,172.00	306,133.00
Total Emissions [kT CO ₂]	0.02	0.19	0.019	1.41
Cost/m ³ [€]	0.43	0.32	0.42	0.31
Emissions/m ³ [kg CO ₂]	2	1.46	1.9	1.41
Number of Cycles	3	28	3	223
Duration of Cycle	3 h 5 m	3 h 5 m	2 h 59 m	2 h 59 m

Table 5.4: Results model runs dredging operations Land Raise

	Nieuwe Waterweg (Trucks)		Nieuwe Waterweg (Pipeline)		Maasvlakte (Trucks)		Maasvlakte (Pipeline)	
Volume	10k	130k(full capacity)	10k	130k(full capacity)	10k	1M(full capacity)	10k	1M(full capacity)
Total Time [h]	7.63	72.18	7.81	73.97	12.83	948.32	13.02	962
Total Costs[€]	4,421.81	42,128.59	4,494.50	42,835.25	6,479.91	479,719.26	6,554.00	485,259.99
Total Emissions [kT CO ₂]	0.02	0.20	0.02	0.20	0.03	2.24	0.03	2.26
Cost/m ³	0.44	0.32	0.45	0.33	0.65	0.48	0.66	0.49
Emissions/m ³ [kg CO ₂]	2.09	1.53	2.13	1.56	3.02	2.24	3.06	2.26
Number of Cycles	3	28	3	28	3	223	3	223
Duration of Cycle	2 h 35 m	2 h 35 m	2 h 40 m	2 h 40 m	4 h 15 m	4 h 15 m	4 h 20 m	4 h 20 m

5.4. Land Raise

The Land Raise case is the first alternative implementation analysed. The implementation itself is relatively simple, as it only requires placing the sediment on land and waiting. One of the key interesting factors come from the different methods for moving sediment over land that are simulated.

5.4.1. Dredging

Where in the BaseCase the routes for dredging operations were relatively similar in length, they are significantly different in length for the Land Raising case. [Figure 5.2a](#) shows that the dredging site is very close to the placement locations in this case. Comparatively, the Maasvlakte is significantly further away as shown in [Figure 5.2b](#). This difference in distance should be visible in the dredging figures. The Gantt Charts for the dredging operations in [Figure 5.3a](#) and [Figure 5.4a](#) shows that completing a single cycle takes just over 2.5 hours for the Nieuwe Waterweg location, but over 4 hours for the Maasvlakte source. Furthermore, as the anchorage for the pipeline is slightly further from the dredging sources it can be seen that the cycles for the pipeline anchorage take about 5 min longer than those aiming for the groyne cell placement. Finally, comparing [Figure 5.3](#) and [Figure 5.4](#) to the gantt charts for the BaseCase in [Figure 5.1](#) it is notable that the unloading activity takes significantly longer. This is because of the need to use the unloading pump rather than the bottom doors.

The dredging numbers from the model can be seen summarised in [Table 5.4](#). Some interesting details emerge, notably as expected the costs and emissions for Maasvlakte dredge are significantly higher than for Nieuwe Waterweg dredge, this is as expected, however, the costs and emissions for Maasvlakte dredge are also significantly higher than for the BaseCase. This difference can be explained by the longer route the vessels have to travel for the Land case than the BaseCase. This as such also means that regardless of land transport this will always be less efficient than the BaseCase for Maasvlakte dredge. Nieuwe Waterweg dredge is notably not really any more efficient than in the BaseCase even though the route is significantly shorter, this is due to the fact that dredge offloading through pumping is much less efficient than bottom door unloading, not just in time required but also in power demand.

5.4.2. Truck Transport

A key method of moving soils materials across land is through trucks. After the dredge material has been placed in the groyne cell by the dredging vessel, it can be moved into trucks with the help of diggers or cranes. As covered in [chapter 4](#) the results are split over the various stages of the process and the land transport stage to a drying location is one. The route the trucks (see [Figure 5.5](#)) take is

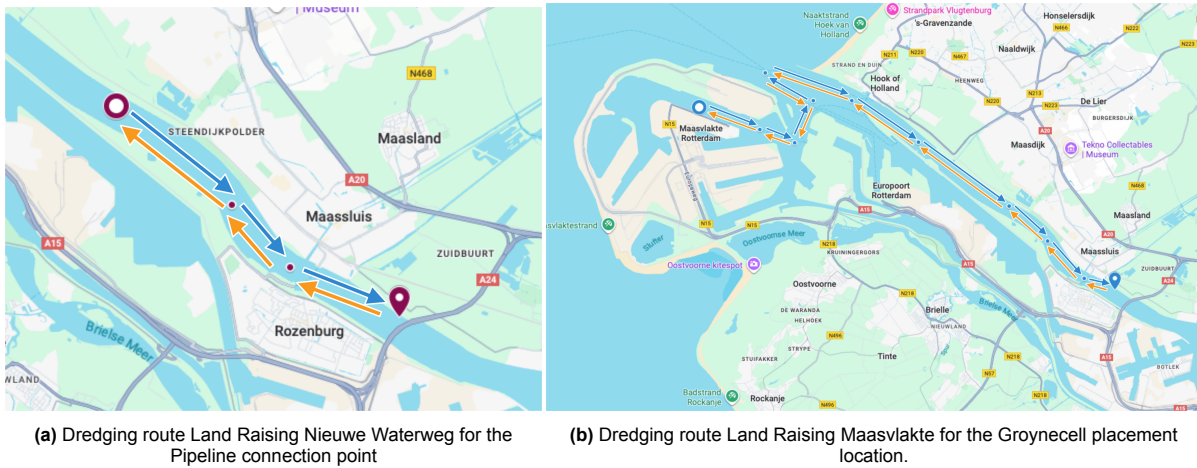
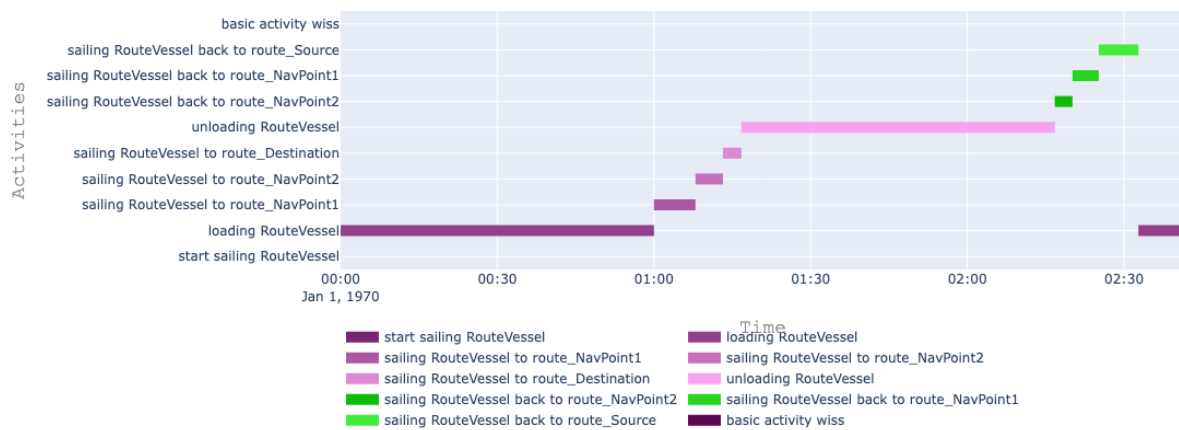
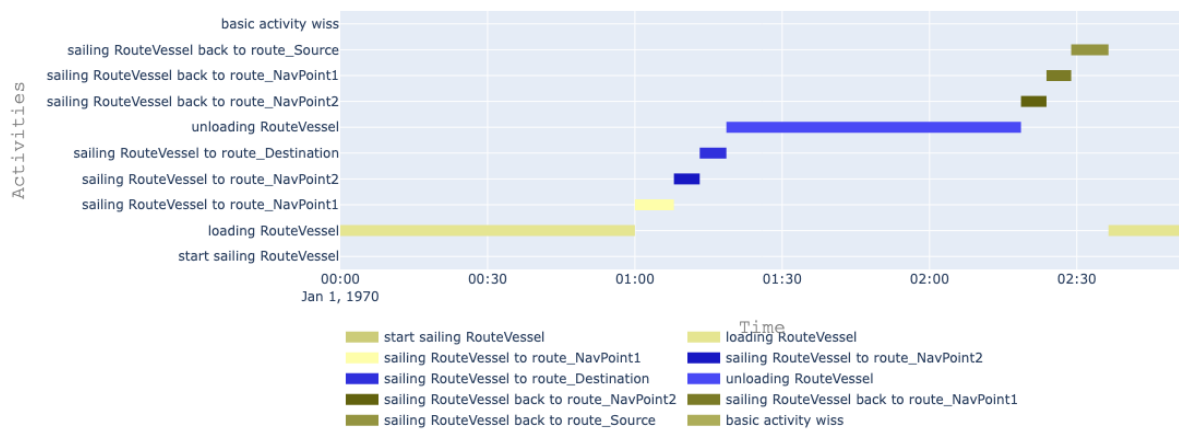


Figure 5.2: Maps showing the dredging routes for the Land Raising case; Placement direction in blue arrows and return route in orange



(a) Gantt Chart for the Nieuwe Waterweg dredging operations for groyne cell placement.

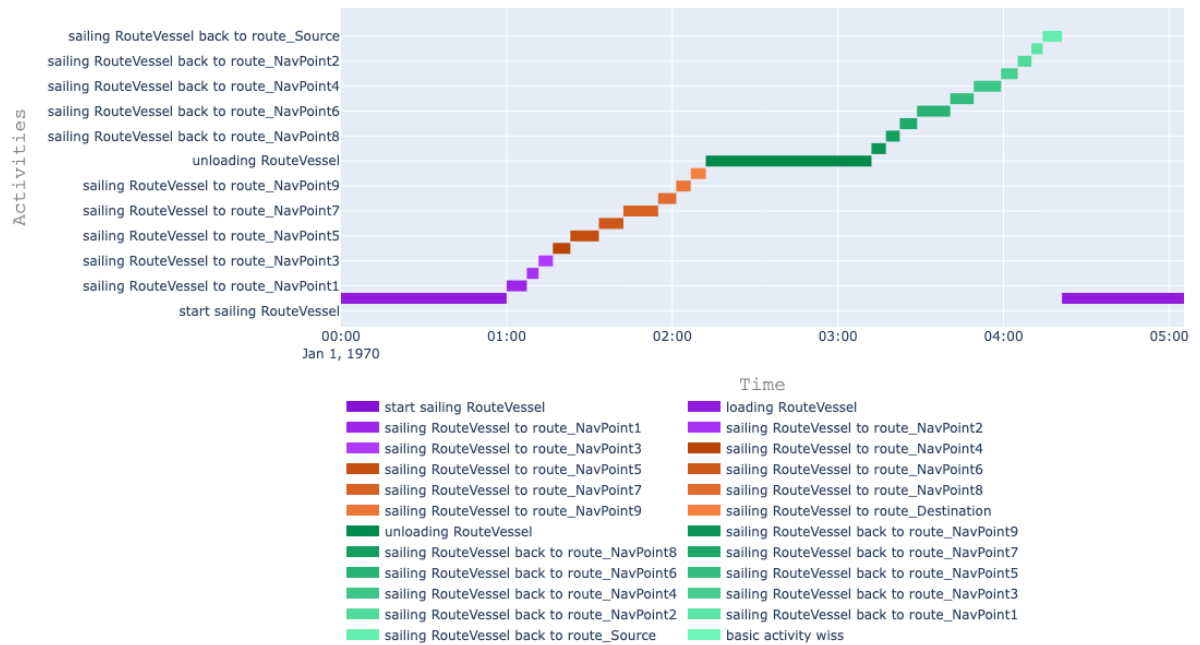


(b) Gantt Chart for the Nieuwe Waterweg dredging operations for the pipeline anchorage.

Figure 5.3: Gantt Charts for the Nieuwe Waterweg dredging operations



(a) Gantt Chart for the Maasvlakte dredging operations for groyne cell placement.



(b) Gantt Chart for the Maasvlakte dredging operations for the pipeline anchorage.

Figure 5.4: Gantt Charts for the Maasvlakte dredging operations



Figure 5.5: Map showing truck route from groyne cells to placement polder (purple) and Pipeline from anchorage to placement polder (orange)

Table 5.5: Results model runs Land Raise

	Nieuwe Waterweg (Trucks)		Nieuwe Waterweg (Pipeline)		Maasvlakte (Trucks)		Maasvlakte (Pipeline)	
Volume	10k	130k(full capacity)	10k	130k(full capacity)	10k	1M(full capacity)	10k	1M(full capacity)
Dredging Time [h]	7.63	72.18	7.81	73.97	12.83	948.32	13.02	962
Dredging Costs[€]	4,421.81	42,128.59	4,494.50	42,835.25	6,479.91	479,719.26	6,554.00	485,259.99
Dredging Emissions [kT CO ₂]	0.02	0.20	0.02	0.20	0.03	2.24	0.03	2.26
Secondary Transport Time [h]	295.46	3840.91	n.a.	n.a.	295.46	29545.46	n.a.	n.a.
Secondary Transport Cost[€]	38,823.85	504,615.11	4,516,967.78	4,557,855.21	38,823.85	3,881,530.45	4,516,967.78	4,875,188.34
Secondary Transport Emissions [kT CO ₂]	0.01	0.073	0.62	0.69	0.01	0.56	0.62	1.18
Total Cost/m ³	4.65	4.26	452.47	35.45	4.85	4.56	452.68	5.56
Total Emissions/m ³ [kg CO ₂]	2.73	2.10	64.17	6.84	3.66	3.17	65.10	4.46

about 4.7 km long. Standard soil transport trucks have a capacity of 22 m³ and the roads between the groyne cells and placement location are mostly 50 km h⁻¹ max roads. In order to estimate travel time, google maps was used. The model using all this information, fuel efficiency estimates, and digger process estimates calculates the truck transport process.

Table 5.5 shows the model results for the land raise case, where Secondary transport refers to the outputs related to the truck or pipeline transport. Notable is that due to the limited capacity of the trucks vs the dredging vessel the amount of transport time is significantly higher, upwards of 50 times the dredging time. This is not that strange considering the capacity difference is more than 200 times. The per unit cost remain quite high compared to the BaseCase, mostly due to the rental and operating costs of trucks, which can't really have any scale efficiency gains. As the trucks operate by usage time and the usage time is dependent on the total volume and the truck capacity this is a linear relationship. This non scaling nature can also be seen when comparing the Maasvlakte and the Nieuwe Waterweg, even though the total volume is much higher the values maintain a similar offset, mostly due to the extra distance of the dredging operations. Notably, though the emissions are higher per unit than the BaseCase the difference is nowhere near as bad as for the cost. It seems that though trucks could move the sediment, they are quite an expensive method and not very time efficient.

5.4.3. Pipeline

Alternatively to moving all the sediment by truck, a pipeline could be installed as explained. The pipeline would be installed along the route shown in Figure 5.5, which runs along a highway and connects at a dock installed for the tunnel construction. Of course a pipeline would be a significant upfront investment and the cost estimate for this pipeline is 4 500 000 € with an operating and maintenance cost estimate of 75 000 € per year. Furthermore, as the pipeline is assumed to have a supporting pump it is assumed there is fuel consumption and some supporting crew.

Table 5.5 shows the combined construction and operating costs for the pipeline. The costs clearly start very high due to the construction costs and as such the 10k runs obviously end up with exceptionally high costs per cubic meter. However, the drop in per unit cost is already significant when looking at the Nieuwe Waterweg at full capacity, and when evaluating the Maasvlakte at full capacity it is close in price

to the Truck per unit costs. As the construction of the pipeline has of course emissions connected to it, these also start significantly elevated for lower volumes. However, they also clearly reduce significantly at larger volumes. Both of these decreases are clearly significantly larger than what would be expected for an efficiency gain as seen in the BaseCase, as such it seems there is a clear benefit of scale when implementing a pipeline. The pipeline clearly is still not as cheap or low on emissions as the BaseCase however that is to be expected given that additional steps besides the dredging are involved.

5.4.4. Comparison Trucks vs Pipelines

The results show a clear trend that the pipeline rapidly approaches the trucks regarding emissions and costs. As a pipeline is a long term project that could be used for multiple years it makes sense to see how this trend continues over multiple years and if eventually pipelines become cheaper and less emission intensive than trucks. To this end extra runs were performed for up to 10 000 000 m³ of sediment for each location. Figure 5.6 shows the cost and emission results of these runs. Each graph has the Pipeline, Trucks, and BaseCase values plotted. Figure 5.6a shows that the pipeline becomes cheaper than trucks per cubic meter of sediment after about 8 000 000 m³ or about 8 years. It takes a similar amount of sediment for the cost to equalise for the Nieuwe waterweg (Figure 5.6c), however that is about 60 years of sediment and thus not really worth the investment. The emissions are even faster, after around a year the emissions break even for the Maasvlakte case (Figure 5.6b) and after about 6 years for the Nieuwe Waterweg (Figure 5.6d). As such a pipeline could very quickly start to make sense when it is a multi year sediment processing plan. Especially, when concerning the volume amounts found at the Maasvlakte.

The figures also show that there is a plateauing effect where the pipeline cost and emissions ends up in between the BaseCase and the Trucks. The costs and emissions never drop below the BaseCase and this makes sense given that this application requires additional transport and thus investments to process the sediment. The lowest cost per cubic meter that can be achieved for Maasvlakte dredge is €3.30 for the pipeline and €4.56 for truck transport. Nieuwe waterweg dredge can get down to €4.26 for Trucks and €3.14 for Pipeline transport.

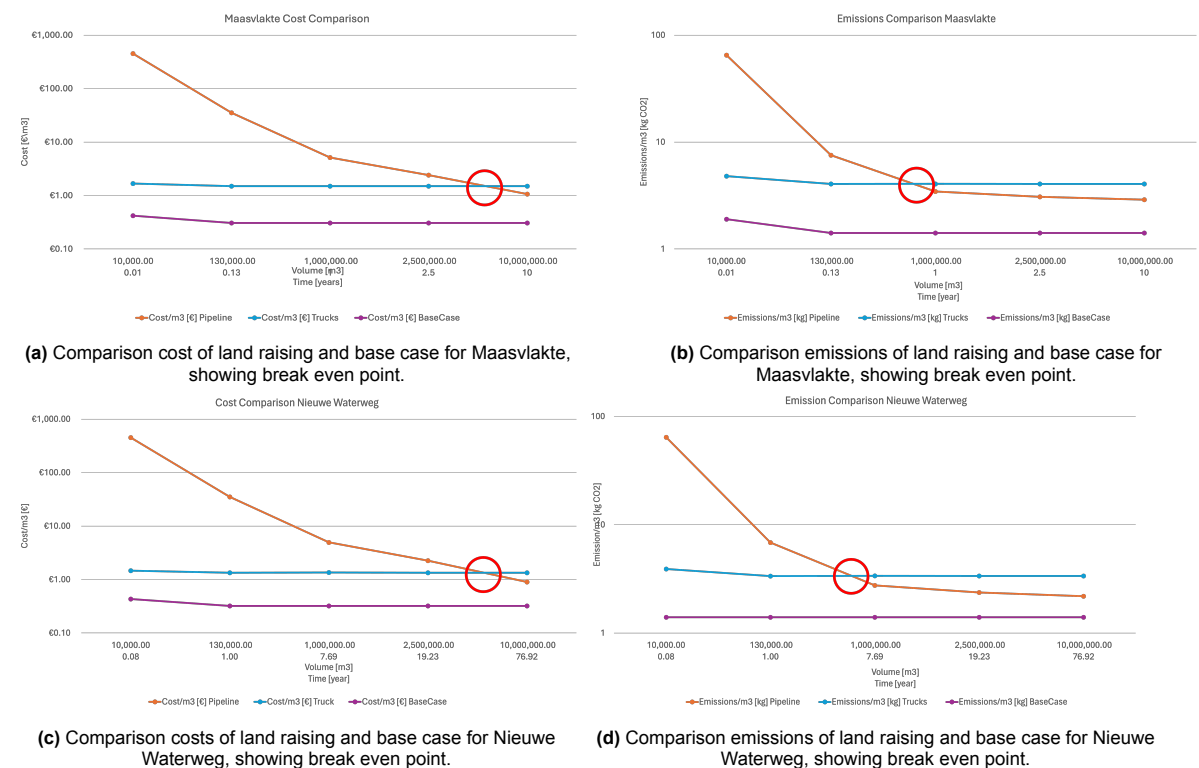


Figure 5.6: Graphs comparing Land raising case to base case for both dredge sources



Figure 5.7: Map showing the route for the sediment over land, purple indicates the route from onshoring to drying location, and light blue the route from drying to concrete manufacturer.

5.5. Concrete

The concrete case partially has strong similarities to the land raise case, especially when it comes to the passive drying methods. Passive drying methods — Pond and Nature supported drying — are performed at the same location as the Land case. As the comparison of transport methods was done for the Land Case this is not redone for the concrete case, as such all transport is assumed to be done with trucks. The dredging routes are again as shown in [Figure 5.2a](#) and [Figure 5.2b](#), although now only the location of the groyne cell placement is considered. The Final destination for the sediment was selected as Struyck as explained [Final destination](#) it is the closest concrete manufacturer that has experience with alternative materials. This means that the route the sediment takes after it leaves the dredging vessel is as shown in [Figure 5.7](#). The purple route showing the familiar truck route to the drying location, and light blue indicating the route from drying to the sediments final destination at the concrete manufacturer. It is assumed the hypothetical external company performing the mechanical dewatering is at the same distances from the groyne cells and concrete manufacturer to facilitate easier comparison between the alternatives.

The results for dredging operations and secondary transport ([Table 5.6](#)) are as expected the same as for the land increase case ([Table 5.5](#)). The tertiary transport values are clearly significantly lower than those for the secondary transport, this is because sediment loses about 50% of its volume when the water is removed, as such only 50% the volume has to be moved after dewatering and as shown in [Table 5.6](#) the costs and emissions are around 50% of those for the Secondary Transport. The difference is not actually 50% as the distances of transport are different, dried sediment has a slightly longer route to travel to the concrete manufacturer than the wet sediment to the dewatering location. It is notable that Secondary and Tertiary transport are in all cases a majority of the costs and emissions suggesting that limiting these distances is a key gain for overall efficiency of the concrete implementation.

As the transport outputs are the same for all drying methods the more interesting comparison comes from evaluating the sediment processing outputs. Pond drying is for the volumes of Nieuwe Waterweg really quite efficient as it completes in around 15 days, this is because the selected area for drying is $1\,200\,000\text{ m}^2$ which means the resulting layer is only about 11 cm which allows the sediment to dry very quickly. The volume of the Maasvlakte takes over 250 days to dry, this is almost 17 times as long, clearly showing thicker layers take longer. A similar picture appears for the natural case, though overall the process is clearly significantly faster, only needing a few days for Nieuwe Waterweg sediment and just under a month for Maasvlakte sediment. As emissions from the dredge itself are left out of

the analysis only Pond and External drying have emissions from the drying process. Pond because diggers are utilised in aerating the sediment and External as the electricity used to operate the business is not necessarily emission free. The External case is by far the fastest given its very high per hour processing capacity of over 2450 m³ of sediment. Notably, this is over 100 truck loads of sediment. This speed does come with a price premium of around €4,- per cubic meter. However, even this high pricetag is not the major cost in this implementation and transport remains the biggest cost, as such if a dewatering facility could be constructed much closer to the shipping channels this would bring the cost much closer to the passive dewatering techniques.

The gains that can be made for large scale implementations by moving the wet sediment with a pipeline are unfortunately not applicable to dry sediment. Dry materials can be moved through pipelines but it is significantly more difficult. As such the transport of the dried sediment will always need to be done by other means, push barge transport would be far desirable, but is not possible at this location for the dewatering field.

Table 5.6: Model Results Concrete

Drying Method	Nieuwe Waterweg (130k)			Maasvlakte (1M)		
	Pond	Nature	External	Pond	Nature	External
Dredging Time [h]		72.18			948.32	
Dredging Costs[€]		42,128.59			479,719.26	
Dredging Emissions [kT CO2]		0.20			2.24	
Secondary Transport Time [h]		3840.91			29545.46	
Secondary Transport Cost[€]		504,615.11			3,881,530.45	
Secondary Transport Emissions [kT CO2]		0.12			0.92	
Sediment Processing Time [h]	350.4	86.4	52.91	6083.33	948.32	407
Sediment Processing Cost [€]	7,555.39	30,403.97	587,142.86	199,920.00	261,986.30	4,516,483.53
Sediment Processing Emissions [kT CO2]	0.01	0.00	0.01	0.01	0.00	0.11
Tertiary Transport Time [h]		2146.76			16513.54	
Tertiary Transport Cost[€]		279,277.95			2,147,787.73	
Tertiary Transport Emissions [kT CO2]		0.04			0.28	
Total Cost/m3	6.41	6.59	10.87	6.71	6.77	11.03
Total Emissions/m3 [kg CO2]	2.74	2.73	2.84	3.45	3.44	3.54

5.5.1. Passive drying methods

The results already showed that layer depth of drying material in Pond and Nature supported drying had a significant impact. In order to clarify this relations some additional runs were performed. These runs assumed a drying field of 200 000 m² and sediment volumes of 66 000 m³, 100 000 m³, 200 000 m³, 300 000 m³, and 400 000 m³ corresponding to layer depths of 33 cm, 50 cm, 100 cm, 150 cm, and 200 cm respectively. These runs use the Maasvlakte as source, though this is mostly irrelevant, as is the secondary transport, as the only outputs of interest are the sediment processing ones to create a clear picture.

The results clearly show the quadratic relation between dewatering time and layer depth, [Figure 5.8](#) shows the larger the volume placed and as such the thicker the layer the longer it takes to dry. The pond methods — where the assumption is that a one meter layer takes 1 year to dewater — skyrockets to 4 years when that layer depth is doubled. By dividing the volume in question with the amount of time required we get the total drying capacity per year. This capacity is the total amount that could be dewatered by depositing sediment in layers. As such using thinner layers leads to a significantly larger capacity. The story is similar when doing nature supported drying, although the scale is even larger due to the reduction in time required. By plotting these results in a graph ([Figure 5.9](#)) it becomes very clear that increasing the layer thickness rapidly increases the drying time required and decreases total capacity of the plot of land.

		Available land	200,000.00				
		Layer depth	0.33	0.50	1.00	1.50	2.00
		Volumes	66,000.00	100,000.00	200,000.00	300,000.00	400,000.00
POND 1 m = 1 year 	Drying time [days]	40.15	91.25	365.00	821.25	1,460.00	
	land cost	€ 3,960.00	€ 9,000.00	€ 36,000.00	€ 81,000.00	€ 144,000.00	
	Digger Emissions [T CO2]	0.50	1.16	4.63	10.42	18.52	
	Total Capacity 1 year	513,874.32	359,502.61	189,438.17	128,570.80	97,301.17	
NATURAL 1 m = 90 days 	Drying time [days]	10.95	21.9	91.25	200.75	361.35	
	Worm Cost	€ 14,850.00	€ 22,500.00	€ 45,000.00	€ 67,500.00	€ 90,000.00	
	land cost	€ 1,080.00	€ 2,160.00	€ 9,000.00	€ 19,800.00	€ 35,640.00	
	Total Capacity 1 year	1,362,620.79	1,134,274.25	654,121.86	473,675.67	363,323.41	

Figure 5.8: Passive Drying Methods comparison

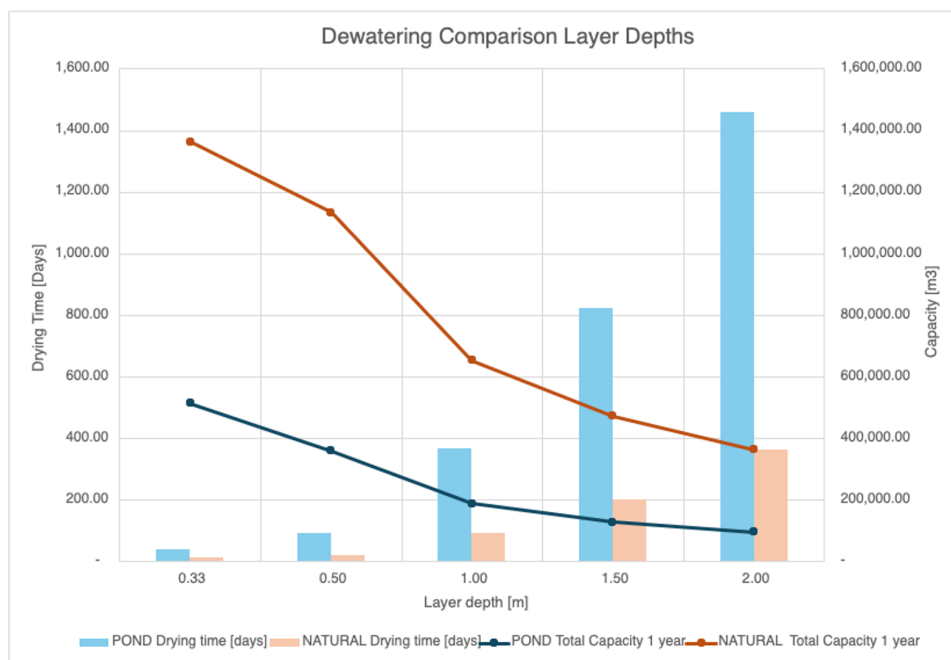


Figure 5.9: Graph showing passive drying methods

Analysis and Interpretation

The model results provide insight in the cost, emissions, and time impact of the implementation methods. This however is only a small part of the total picture. In order to score each implementation on the criteria as listed in [chapter 3](#) the criteria need to be ranked by how the stakeholders value them regarding choosing new implementations. All the cases also need to be scored for each criterion in order for a final ranking to be given to each case.

6.1. Method

Stakeholder input for this research was collected in various methods. As the research was performed as part of a PRISMA 3 consortium project, numerous informal conversations with various stakeholders provided valuable insights in creating a deeper understanding of the way PoR operates and the relationships between stakeholders and each stakeholders responsibility and influence. In order to also collect information in a more structured approach two workshops were held with PRISMA-3 consortium members as part of existing periodical meetings where the stakeholders provide updates on their relevant workpackages.

The first workshop mostly entailed a presentation on the research as planned and suggested with several possibilities of use cases to evaluate. This was relatively early in the process before the model had been completed in the stages of mostly desk research. This workshop was used to collect information on the criteria stakeholders find important when deciding on alternative use cases for dredge sediment. In order to achieve this ranking stakeholders were asked, if they desired to participate, to score the previously determined criteria in order of most to least important. This collection was performed through an digital survey, which also collected employer and inputs for added criteria. Furthermore, informally the participants were asked to comment on the proposed use cases which was used to finalise the selection of use cases to evaluate. This discussion was relatively unstructured and allowed stakeholders to provide their input and thoughts and also respond to each other, allowing for open discussion.

The second workshop was towards the end of the project and for a large part was presenting the modelling results to the PRISMA-3 consortium members including the scoring based on their previous input. At the end of the presentation, the participants were divided over breakout rooms to discuss one of three topics that were selected based on the results as interesting learnings. The selection of topics, and breakout room division was done by discussing with the supervising researcher from Deltares, and the PRISMA session organiser also from Deltares. The selected topics were selected as these were considered the learnings from the research most of interest to discuss with the stakeholders. The best performing solution, the relation between drying time and layer depth for natural methods, and generally benefits of scale. The groups were divided to have as equal a representation of stakeholder groups as possible in each breakout room. Each group got one of the topics to discuss in an open discussion, with one of member of the planning group supervising each meeting and taking notes.

6.2. Stakeholder assisted Scoping - Workshop 1

In order to filter the cases under evaluation some input from the stakeholders was acquired. The input was valuable as the stakeholders also have more experienced insights into what is feasible in the Port of Rotterdam area. The main input was provided after a presentation of several alternative cases. The main options under consideration initially were: BaseCase, Land Raising, Salt Marsh Construction, Artificial Islands, Groyne Cell Habitat creation, and Concrete.

The stakeholders in the questions were representatives of the organisations involved in the PRISMA 3 consortium: Port of Rotterdam, Deltares, Rijkswaterstaat, Boskalis, Van der Kamp, Van Oord, and TU Delft. PoR had 6 representatives including several in manager roles, Deltares had 2 representative being specialists, Rijkswaterstaat had 3 representatives including one advisor, the dredging firms — Boskalis, Van der Kamp, and Van Oord — had a total of 4 representatives including a project engineer and operations manager. This representation is not necessarily the highest managers with full decision making power but they do represent knowledgeable agents in their organisations and could significantly influence decisions if they are not taking them. The Consortium has several research projects ongoing in the Port of Rotterdam area, and most of the member organisations also operate a significant amount of business in the area, as such they are very knowledgeable about the region and its possibilities. In discussion with the Consortium it became clear that any possible location for salt marsh construction would be quite far from the PoR dredging locations and significantly closer to other dredging locations. As such, it would make more sense to use more local sediment for those projects and leave them out of consideration for this research. Artificial islands have a similar limitation that due to the operational nature of the PoR and high density shipping there are no significantly sized, suitable locations in the area. Groyne cell habitat creation, though interesting has a key limitation that there are only so many groyne cells available in the PoR area and the total estimated capacity is around $1\,000\,000\text{ m}^3$. This is the yearly amount of sediment that is of interest to be processed, however, the PoR is interested in determining long term candidates that could be used to process that volume yearly. As such, this application was also placed outside of scope.

The Land Raise case and Concrete case were indicated as the most interesting by the stakeholders. Land raising unlike salt marshes has more flexibility in its placement locations, as such is more suited to the PoR area. Finally, stakeholders (especially the PoR) expressed an explicit interest in the possibilities of the concrete case. Concrete is one of the biggest emission factors for the PoR as it is almost constantly doing construction. The three key emission factors for the PoR are Steel, Concrete, and Dredging. An application that could potentially reduce the emissions of two of these three main contributors is very desirable. Furthermore, shipment of materials is often not considered in the emission analysis of businesses, and even though this can't be compared as such, using more local materials would significantly reduce this factor.

Thus the final scope for implementations under consideration is: BaseCase, Land Raising, and Concrete base material.

6.3. Stakeholder ranking - Workshop 1

In order to rank the alternative implementations according to the decision making criteria first it has to be determined how the stakeholders weigh each criterion. This ranking was achieved by asking the stakeholders in a consortium meeting to order the list of criteria in order of importance according to them. At this meeting there were 6 representatives of PoR, 4 from dredging firms, 3 from Rijkswaterstaat, 1 contractor, and 2 from Deltares. The answers were combined per stakeholder in order to create a single representation of each stakeholder. Furthermore, the results for all stakeholders are combined to see how the mean of all stakeholders favours the different criteria, and a combination of PoR and RWS was created as they are the only stakeholders present who actually have decision making power.

Figure 6.1 shows the rankings of each stakeholder where 1 is the most important and 8 the least. It can be seen that overall the stakeholders are quite aligned on the importance of criteria. Some stronger deviations can be seen as well, Deltares clearly values sustainability higher than the other actors, Rijkswaterstaat finds bureaucratic difficulties more important than the others, and a significant spread is seen at the ranking of safety. Besides these differences it is mostly notable how well aligned the stakeholders are, this may of course be partially because all of the representatives present were part

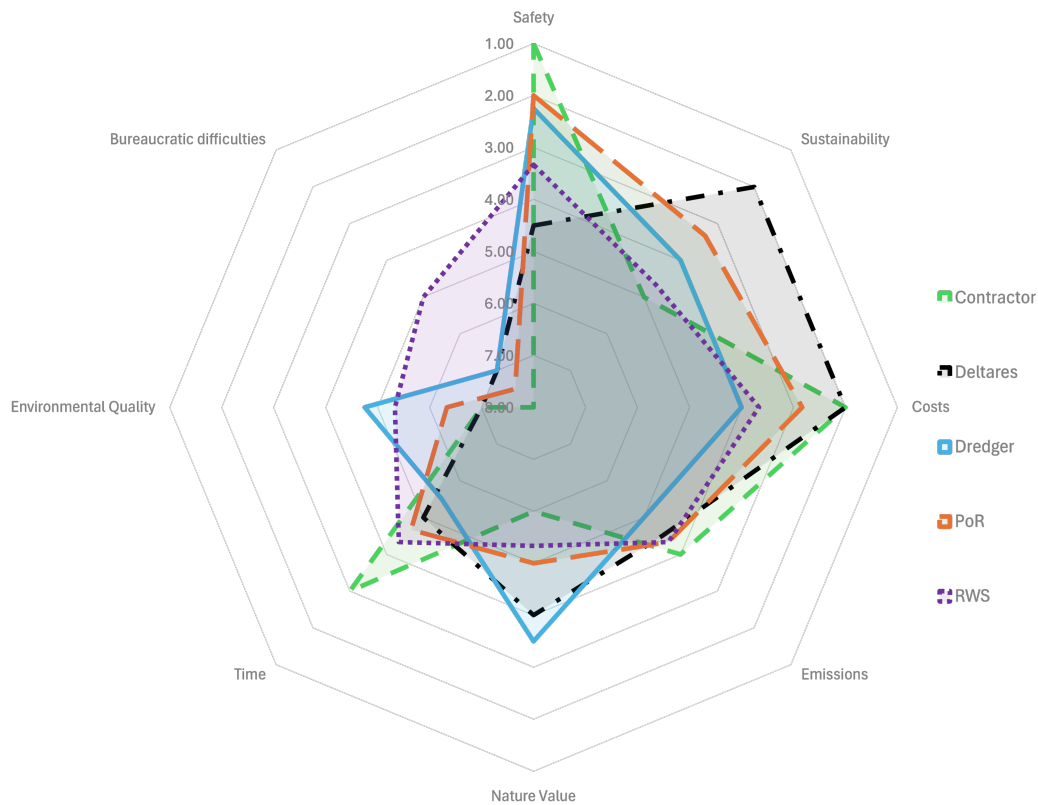


Figure 6.1: Spider diagram showing overview of stakeholder rankings per stakeholder(group)

of the same consortium and thus have at least partial alignment on their ideas. The overall comparability of the results likely means that the final scoring of the use cases will be quite similar. However, before the use cases can be ranked using the priorities of the stakeholders it is important to see how the scoring of the key decision makers compares, and all stakeholders combined.

Table 6.1 shows the ranking result for each of the stakeholders and how these values combined when considering just the two key decision makers and when combining all stakeholders. The colourcoding is done on the scale of 1 to 8 where lighter is closer to one and dark closer to eight. It is notable that the more people were in a stakeholder group, the closer the values get to average, while maintaining some similarities. Bureaucratic difficulties and Environmental qualities score low importance with all most all stakeholders and are the lowest two for both the combined score for PoR and RWS and for the total score of all stakeholders. Furthermore, safety and costs score the highest for almost all groupings, except for the dredger who does not rank cost as highly, which is might be as they are contracted to do the work and the costs don't necessarily impact them all that much.

In order to use these rankings to determine the most desired solution, the ranks have to be transformed to weights. These weights can be multiplied with the scores each solution receives per criteria, in order to acquire a total score per solution. The weights need to be lower for higher ranks as those are the less important criteria. In order to achieve this the weights are determined as seen in Equation 6.1 where w_i is the weight for a particular rank r , normalised so all weights sum to 1. The weights can be used for the final scoring after scoring each implementation per criteria, as covered by the next section.

$$w_i = \frac{\frac{1}{r_i}}{\sum_j \frac{1}{r_j}} \quad (6.1)$$

Table 6.1: Table showing average ranks given by each stakeholder and combinations of stakeholders, cells are colour coded on a scale of 1-8 lighter lower darker higher. Ranking where 1 is most important and 8 least.

Organisation	Contractor	Deltares	Dredger	PoR	RWS	PoR + RWS	Total
Safety	1.00	4.50	2.25	2.00	3.33	2.67	2.56
Sustainability	5.00	2.00	4.00	3.33	4.67	4.00	3.69
Costs	2.00	2.00	4.00	2.83	3.67	3.25	3.13
Emissions	4.00	4.50	5.00	4.33	4.33	4.33	4.50
Nature Value	6.00	4.00	3.50	5.00	5.33	5.17	4.63
Time	3.00	5.00	5.50	4.67	4.33	4.50	4.75
Environmental Quality	7.00	7.00	4.75	6.33	5.33	5.83	5.88
Bureaucratic difficulties	8.00	7.00	7.00	7.50	5.00	6.25	6.88

Table 6.2: Scoring of all implementations

	Cost	Emission	Time	Safety	Sustainability	Nature Value	Environmental Quality	Bureaucracy
BaseNW	4.99	4.93	4.38	4	2	1	2	5
BaseMV	5.00	5.00	4.49	4	2	1	2	5
ConcNWPO	4.13	2.05	1.00	4	5	3.5	3	1
ConcNWES	1.09	1.92	1.00	4	5	3	3	2
ConcNWN	4.00	2.05	1.00	4	5	3.5	3	1
ConcMVPO	3.95	1.12	1.00	4	5	3.5	3	1
ConcMVES	0.98	1.00	1.00	4	5	3	3	2
ConcMVN	3.88	1.14	1.00	4	5	3.5	3	1
LandNWP	1.84	3.24	5.00	4	5	4	4	2
LandNWT	4.29	2.44	1.02	4	4	4	3	1
LandMVP	4.49	3.07	3.39	4	5	4	4	2
LandMVT	4.19	1.54	1.02	4	4	4	3	1

6.4. Scoring implementations

Having established the scoring criteria and their weights, each implementation has to be scored for each criteria. The implementations will be given a score from 1-5 for each criteria and those scores can be combined to determine which implementation performs best.

6.4.1. Model Outputs

In order to determine the Cost, Emission, and Time scores the outputs of the model can be reordered to fit the scale of 1-5. This means for the costs that the cheapest implementations would get a score of 5 and the most expensive a score of 1, the same goes for emissions and time.

The results of this scoring can be seen in [Table 6.2](#). As expected the BaseCase implementations score very highly for Cost, Emissions, and Time. Notably, the pipeline land raising case for Nieuwe Waterweg scores highest on time, which is due to the very short distance the vessel have to travel and the sediment volume being low enough that it can dry very quickly. The Land raising cases mostly score highly on cost too, though the Nieuwe Waterweg pipeline does not have the scale benefit to score well. None of the implementations outperform the BaseCase on emissions and they also don't come that close, which makes sense as all implementations add additional steps and as such add additional sources of emissions.

6.4.2. Non model criteria

Having scored the criteria that were determined from the model results, the other criteria need to be scored. As these criteria are not really dependent on dredging source but more so on implementation, this section will discuss those criteria per implementation case. All of these scores and their justifications can also be found in the tables in [Appendix D](#).

BaseCase

The basecase is how the Port of Rotterdam currently operates, as such it would be expected to score relatively high on all categories. The BaseCase is unlikely to score critically low as in that case it should never have become the status quo. This also mean that it scores perfectly on bureaucratic difficulties as they aren't present, all the legislation has been sorted and no difficult processes have to be worked

out.

Safety, Sustainability, and Nature values have similar aspects impacting their score. The BaseCase is considered to be very safe and unlikely to have an major risks, as the sediment is tested regularly. However, forever chemicals — such as PFAS — have in the past been considered safe and more recently after long term environmental spreading been outlawed. This happened even though research had been around for a long time stating these chemicals were likely not safe. As such it lost a point for safety as similar things could occur again. The placement of sediment also creates a large amount of turbidity and is disruptive to the bentic life, this is considered acceptable by the Dutch Government, but nonetheless this was decided to set a low score as the process is only destructive to local nature. Sustainability ends up getting a low score as longer distance shipping as is required just creates high emissions. The score is pulled up a little because the placement feeds the global sediment systems and supports the continued existence of the Waddenzee. Finally, environmental quality scores relatively low as it again doesn't provide any local benefits but also doesn't create any possible problems for people to complain over.

Land - Pipeline

The land increase case will be similar between trucks and pipelines, however there will be key differences. Once again the safety score is really quite high, as the sediment is regularly checked and evaluated. Some more possible risks could arise with the construction of the pipeline or the dikes surrounding the polder. However, these risks are considered to be negligible as these are tried and tested methods that Dutch experts have perfected. This method scores very high for sustainability as it places the sediment on land as would have happened through natural river deposition. Furthermore, it has the potential to reinvigorate the agriculturally depleted soil, and while the sediment is drying, marsh bird can enjoy additional habitats. Unfortunately, the drying sediment ponds do look rather ugly as they are mostly large grey fields, so this reduces the environmental quality somewhat, but only temporarily during the drying stage. The regenerative potential for the soil is also great for the nature value and thus scores highly there. Finally, This implementations scores quite low regarding bureaucracy as quite a few parties would have to be convinced in order to facilitate this implementation. The pipeline itself shouldn't create too many hurdles as it would be placed along a highway which is already present, and would mean no increase in nuisance experienced by the nearby residents. However, the same can not be said for the polder, as landowners, RWS, and local government would have to agree. Furthermore, local residents need to be convinced otherwise the Not In My Back Yard problem may lead to significant issues and delays. One slight advantage is that sediment placement on land is the oldest method of management employed in dutch waterways, and still the main method for most smaller local waterways.

Land raising - Trucks

The truck implementation scores relatively similar to the pipeline case for several of the criteria. Safety and Nature Value score the same as they mostly related to the final placement and that is identical. However, as the trucks require significantly more supporting equipment, it is a less sustainable way of organising this implementation.

The largest problem trucks have is their limited transport efficiency. $1\,000\,000\text{ m}^3$ in sediment a year with trucks that have a capacity of 22 m^3 would require $\frac{1\,000\,000}{22} \approx 45\,455$ trips. Assuming around 250 working days in a year that would mean $\frac{45\,455}{250} \approx 182$ truck trips per day. Local roads are not built to support 180+ 25 ton truck loads per day, which means local government would never grant permission. Furthermore, if permission was somehow granted the local residents would likely do whatever they could to stop this from happening as no one wants to have a truck coming by every minute. As such truck implementations score lower on both environmental quality and bureaucracy.

Concrete

The concrete case is unified by the nature of its final product being identical. Though the transport method selected for this analysis was trucks, this is not taken into account as much as for the land case, given that the comparison of transport methods happened there. The concrete cases score the same as the other cases for safety as once again it is possible that some contaminants could make it into the final product but this is deemed unlikely.

Sustainability is a strong suit for the concrete case, as it reduces the need for imported base materials in concrete manufacturing, and utilises local materials for local implementations. This local material

Table 6.3: Final scores of all implementations per stakeholder group; light blue for lowest scores and dark blue for highest scores.

Organisation	Contractor	Deltares	Dredger	PoR	RWS	RWS+PoR	Total
BaseNW	3.25	3.59	3.70	3.49	3.40	3.66	3.60
BaseMV	3.26	3.61	3.72	3.52	3.42	3.68	3.62
ConcNWPO	2.74	2.57	2.64	2.61	2.91	3.18	3.25
ConcNWES	2.69	2.52	2.43	2.49	2.65	2.70	2.75
ConcNWN	2.73	2.56	2.63	2.60	2.90	3.16	3.23
ConcMVPO	2.62	2.44	2.50	2.48	2.78	3.03	3.11
ConcMVES	2.58	2.40	2.30	2.37	2.53	2.58	2.63
ConcMVN	2.62	2.44	2.50	2.48	2.77	3.02	3.10
LandNWP	3.57	3.59	3.53	3.54	3.66	3.64	3.66
LandNWT	2.73	2.63	2.65	2.65	2.92	3.17	3.24
LandMVP	3.57	3.49	3.56	3.52	3.72	3.86	3.90
LandMVT	2.63	2.51	2.52	2.53	2.80	3.05	3.12

re-use is also beneficial for environmental quality of the final product as marketability of "green and sustainable" products is higher and consumers see this as a positive. However, the final product is still concrete, and the drying methods are not great scorers like in the land case, as such the environmental quality scores middle of the road. The nature value scores decently, as the drying fields will potentially create temporary habitats for birds, and the final products can be marine habitat creating blocks that can be used in the PoR area. However, as the external drying method does not have the benefits of potentially creating bird habitats this scores slightly lower.

Finally, the concrete case will likely struggle significantly bureaucratically speaking. For the passive drying methods this is for the same reason as in the land cases, which as such does not apply for the external drying. However, the use of dredge as a base material for concrete likely has further legal challenges as the classification of dredge is currently as waste material.

6.4.3. Final Scores

Having scored all the implementations on all criteria the scores totalled using the weights as determined from the stakeholders. For every implementation, each criterion's score gets multiplied by its weight and then the get added together. Table 6.2 shows the final numerical scores for all implementations, to visualise the final results more clearly Table 6.3 displays the scores of each implementation as scored for each stakeholder. Lower scores are visualised with a lighter shade of blue and higher scores with a darker shade. From this we can see that regardless of what stakeholders priorities are used the same cases are the top performers, namely the base cases and the land increase cases with pipeline transport.

The excellent performance of BaseCase implementations does makes sense as it scored quite well on most criteria, Furthermore, it is the current implementation and in an efficiency driven field it is highly unlikely that an inefficient solution remains the standard application. Given that most stakeholders ranked costs, safety, and sustainability as most important, it is not surprising that the basecase that scored well on two of those three does well, on top of which the basecase scored excellent on emissions and time. Notably, the basecase performed slightly less well for Rijkswaterstaat and the Contractor. The contractor is the only stakeholder who has a ranking stretching fully from one through to eight, as a result its weights are more strongly divided and the overall results end up notably different. Rijkswaterstaat on the other hand has scores that are much closer together, due to a higher variance in answers provided by the representatives, as a result the weights are also much more even. This leads to a slightly different distribution in final scores however overall the same solutions perform well. Notably, the land cases actually end up scoring better.

The land cases with the pipeline transport are the other well scoring solutions. Depending on the stakeholder these solutions score even better than the basecase does. Only for the dredger the

Table 6.4: Scores per criteria for each implementation with the final score for the Port of Rotterdam and Rijkswaterstaat combined. The criteria are colour coded in blue with higher scores being darker, the total scores colour coded in orange also the darker the higher.

PoR + RWS weights	Cost	Emission	Time	Safety	Sustainability	Nature Value	Environmental Quality	Bureaucracy	Total
	0.16	0.12078	0.1163	0.196	0.130844786	0.101299192	0.089722144	0.08374066	
BaseNW	4.99	4.93	4.38	4	2	1	2	5	3.66
BaseMV	5.00	5.00	4.49	4	2	1	2	5	3.68
ConcNWPO	4.13	2.05	1.00	4	5	3.5	3	1	3.18
ConcNWES	1.09	1.92	1.00	4	5	3	3	2	2.70
ConcNWN	4.00	2.05	1.00	4	5	3.5	3	1	3.16
ConcMVPO	3.95	1.12	1.00	4	5	3.5	3	1	3.03
ConcMVES	0.98	1.00	1.00	4	5	3	3	2	2.58
ConcMVN	3.88	1.14	1.00	4	5	3.5	3	1	3.02
LandNWP	1.84	3.24	5.00	4	5	4	4	2	3.64
LandNWT	4.29	2.44	1.02	4	4	4	3	1	3.17
LandMVP	4.49	3.07	3.39	4	5	4	4	2	3.86
LandMVT	4.19	1.54	1.02	4	4	4	3	1	3.05

basecase does outperform the land cases, notably they rank cost, emission, and time as less important than the other stakeholders (Table 6.1). This is likely the cause of the different scoring of the final results. This different prioritisation can possibly be explained by the fact that they operate on tenders and as such they simply execute what they are asked to do, and clients pay for the operations.

The main decision holding stakeholders are PoR and RWS, as PoR is the client and RWS is the government institution with the responsibility for water ways and responsibilities for land and water quality. The other stakeholders though involved in this research and the consortium do not actually hold any deciding power. Table 6.4 shows the score table with the weights based on the PoR and RWS combined scoring, it also shows the final score per implementation based on this scoring. The per criteria scoring is colourcoded in blue with better scores being darker in shade. The total scores are colourcoded in orange again with the higher scores being darker.

6.5. Stakeholder Validation

The final results and scores were presented to the stakeholders in order for them to reflect on these outcomes. In this reflection they provided input on if they deemed the results as likely accurate and any notes they had for potential future work, and further considerations. Stakeholders were also asked to reflect on how the results may impact future work, the likely hood of seeing implementations, and areas they still saw as key hurdles.

Stakeholders were divided into three breakout rooms and each discussed one of three topics: Scale benefits, Dewatering relationship, and Top Outcome. o top off this stakeholders got the opportunity to give general comments.

The top outcome discussion, which was about the land case showed concern that even though the rating of the sediment is "altijd toepasbaar - zoet oppervlakte water"¹ that the sediment may not be entirely placeable in the selected environments due to its saline origin. Furthermore, stakeholders expressed the expected insight that reducing the distance to a drying location would be of utmost interest in making any applications worth while. Additionally, this expanded to discussing that a mechanical drying location on the waterfront may be more feasible transport wise and attainable given the nature of the port, with few open green areas close to the shore.

In the other discussions, stakeholders raised a number of specific questions regarding the modelling that due to time had not been addressable during the presentation. Furthermore, some stakeholders were somewhat surprised at the high performing nature of the BaseCase. However, as explained this is expected as it is the main method currently employed and if it scored poorly, the expectation would be that alternative implementations were explored more thoroughly much sooner. Finally, stakeholders expressed some surprise at the benefits gained from placing sediment in thinner layers, and expressed interest in further exploring that approach.

Overall, stakeholders engaged positively with the results and expressed eagerness to further explore

¹English: Always usable - fresh water environment

several avenues of discussion put forth by the research. Some stakeholders did express questions regarding modelling specifics and the input variables used. However, after those questions were answered no further concerns or questions were raised. Finally, stakeholders expressed interest in continuing the exploration of alternative methods using this approach, and given the modular nature of the model, if they have more accurate numbers for some variables, they could easily rerun the analysis.

Discussion and Conclusion

This chapter contains the discussion and conclusion. The discussion will detail the relevance of the final results and how these might impact future decision-making. Furthermore, some key limitations will be discussed, and suggestions for future research that could increase the benefits gained from this research. Following that the conclusion will answer the research questions and provide final recommendations.

7.1. Discussion

This research set out to explore whether participatory logistical modelling can support decision-making and collaboration on beneficial sediment re-use applications for the Port of Rotterdam. Using a combination of stakeholder-defined criteria, detailed logistical modelling, and scenario analysis, the study compared three main implementation pathways — the current Base Case, land raising, and concrete production — each with their own transport and processing variations.

7.2. Implementations

The Base Case remains highly efficient in terms of cost and emissions, this is unsurprising given its optimisation over decades of operational use. However, the alternative implementations, while generally more expensive and emission intensive on a per cubic metre basis, offer broader benefits that the Base Case cannot deliver. Long-term land raising, soil rejuvenation, material re-use in concrete, and potential reductions in the port's total emissions footprint. Notably, nature-supported drying methods and pipeline transport displayed significant benefits of scale over their counterparts, hinting at possible optimisation pathways for future implementations. Though of course the concrete methods generally might end up significantly cheaper if executed with a pipeline. Furthermore, several aspects were not taken into account when considering the alternative cases such as the potential emission savings that could occur in concrete production when using calcined clay (acquired from dredge sediment) vs traditional portland concrete (Cheah et al., 2025). Overall, somewhat surprisingly the Base Case was outperformed by specifically land increase with pipeline transport as such this should definitely be considered further as a potential alternative. Though actual implementation would likely still face significant hurdles with local authorities being sceptical on the cleanliness of the sediment. Furthermore, the shortage of land in the Netherlands may also affect implementations, and owners of land need to be convinced to participate, most likely in a monetary method. The assumption that land can simply be rented for a flat fee, may hold true, however this will heavily depend on the land holders and their desires, which were not considered in this research.

7.3. Stakeholder perspectives

The stakeholder ranking of criteria reveals the inherent tension between short-term operational efficiency and long-term sustainability goals. The weighting of environmental quality, nature value, and bureaucratic feasibility suggests that technical performance alone will not determine adoption. The

ranking input provided by stakeholders may in fact be considered surprising, as it is a common view that businesses only value profits. It is of course also possible that stakeholders are not completely truthful in their answers, as they are aware that this research will be published and as such they may have tried to present a more publicly favoured view. Furthermore, they may not all be the high level decision makers in the business, so the alignment between their views, and their organisations view may differ.

In prior research stakeholders expressed that one of the biggest hurdles in alternative implementations are bureaucratic difficulties (van der Heijde, 2024). Surprisingly, this ended up last in the ranking, suggesting that, though it is a big hurdle, stakeholders do not mind dealing with it, or are willing to go through the process if they expect that the end result is worth it in the other criteria. Finally, it is interesting to see that even though stakeholders disagree on some parts of the ranking, overall they agree mostly on the most important criteria. Furthermore, that even though the rankings were not all that different between stakeholders, the rankings do converge to be closer when combining multiple stakeholders, and that the impact on the scoring of the alternative cases was relatively minor. Overall, the participatory approach proved valuable, allowing stakeholders to see how their priorities align and get more impactful insights in the potential impacts of their decision-making consideration.

7.4. Comparison with literature

While the technical feasibility of alternative sediment re-use applications has been documented in prior studies (Carreira et al., 2025; Solanki et al., 2023), the integration of detailed logistical simulation into a participatory framework for dredge sediment management decision-making has not really been done. As such this is an expansion on existing knowledge regarding both the scaling up of technically feasible alternative use-cases, and the management of stakeholders in dredge sediment decision-making processes. The value of stakeholder participation as expressed by Cutroneo et al. (2014) and L Gerrits (2004) is reinforced by this research as having them participate resulted in clear interest and excitement of stakeholders to take key outcomes from the analysis on board for further development. This shows the benefit of developing implementation plans in active collaboration with stakeholders as also shown by Clifford-Holmes et al. (2017). Furthermore, though a quantitative analysis of course calls in some scepticism regarding accuracy, it also increases interest and participation when those concerns are accurately addressed, which is a particular strength gained from adding detailed modelling steps.

7.5. Strengths and Limitations

The modelling and participatory sessions clearly created an environment where stakeholders could more actively engage in discussion over alternative methods. Furthermore the input from the logistical analysis allowed stakeholders to clearly evaluate and compare the impacts of alternative applications under consideration. Furthermore, the flexible nature of the developed model, and relatively simple user interface allow for easy consideration of more applications in future. The model is entirely built on open source python packages and publicly available data, allowing anyone the opportunity to analyse further implementations. Or if more data becomes available the ability to increase the accuracy of current analysis

However, limitations remain. The model is somewhat simplified to allow for computational ease, and reduce the amount of data that is needed. A key example, is that the dredging operations currently don't have to refuel, or have to wait for shipping lanes to clear. In the real world this is not the case of course, however, these factors could relatively easily be added if so desired. A more significant limitation of the model is that when sediment is placed somewhere, emissions come from the sediment itself due to it having been oxygenated. Data exists for placement on land and in enclosed ponds but no such data exists for placement in open sea. Presumably emissions would not be negligible as they aren't negligible for placement in enclosed water. However, as the analysis was to be comparative, emissions from the sediment would either have to be considered for all cases or none. The main reason this is of concern is that recent studies showed that for placement on land the emissions from the sediment itself far outweigh those of the dredging operations, upwards of 99% of measured emissions came from the sediment itself (Besseling et al., 2021). Besides model limitations, there is also a key limitation, in the stakeholder involvement. Stakeholder involvement in this research was limited to existing members of the consortium, when in considering applications in local areas near peoples residences their input

should also be considered. Expanding the stakeholder group would also add significant complexity in finding participants and organising sessions. This however would be a good avenue of future analysis. Finally, no economic or other emission based gains of any implementations are considered in this research, for example, raising land would normally require significant investment in soil materials. Furthermore, concrete is a very significant market and base materials may be marketable, which could recover additional costs from less efficient implementations. As mentioned, the potential emission savings from using dredge sediment in concrete are also not considered.

7.6. Implications and future directions

The results suggest that while no alternative outperforms the Base Case on all criteria, there is definitely value to be found in further exploring possible implementations. For example, combining elements, such as pipeline transport with nature-supported drying, could offer a more balanced compromise between cost, emissions, and environmental benefits. Future work could further explore emissions modelling from the sediment placements, incorporate economic valuation of ecosystem services, and extend the participatory process to include a broader range of non-technical stakeholders, such as local communities and environmental NGOs. Scaling the approach to other ports would also test the generalisability of the framework and reveal location-specific constraints.

In short, this research demonstrates that participatory logistical modelling is not a silver bullet, but it is a powerful lens through which complex, multi-stakeholder sediment management decisions can be explored, understood, and — potentially — agreed upon.

7.7. Conclusion

Finally, time to answer the questions from the beginning:

“Does participatory logistical modelling provide useful insights for facilitating decision making and collaboration on beneficial sediment re-use applications for the Port of Rotterdam?”

What stakeholders are relevant in decision-making for the sediment management strategies of the Port of Rotterdam and do they have the capacity to significantly influence decision-making?

This depends on the specific cases applied for the sediment. The key decision-makers are the Port of Rotterdam and Rijkswaterstaat. In cases where land is used to dry sediment local municipality and land owners become additional high power stakeholders. Concrete cases see the addition of industry partners like a concrete manufacturer an potentially and external sediment drying firm, finally of course the end product client would be a key stakeholder. **What are key criteria for the varying stakeholders to decide whether or not to participate in implementing an alternative sediment management approach?** The key criteria were identified as: Safety, Costs, Emissions, Time, Sustainability, Nature Value, Environmental Quality, and Bureaucracy. These criteria appeared from existing literature exploring dredge sediment processing alternatives in the PoR area. Stakeholders were during the process of this research given the opportunity to add to the list but no suggestions were given multiple times and as such none were added.

How do stakeholders rank the criteria in importance for decision-making? Stakeholders were asked to rank the criteria and provided the ranking as shown in ???. In order they are: Safety, Costs, Sustainability, Emissions, Nature Value, Time, Environmental Quality, and Bureaucracy.

What are the impacts of the alternative sediment management solutions according to logistical modelling? The logistical modelling showed that essentially no cases were superior to the BaseCase however this is not unexpected. Some high performers were Land Increase cases utilising Pipelines for transport. Though scale was clearly a very important factor here. Other key take-a-ways were, that truck transport is highly inefficient and layer depth is critical in passive drying techniques.

How does a participatory logistical model effect stakeholders understanding of the sediment management problem? Stakeholders that were involved in this research generally responded well to the model, most stakeholders were also technical experts and as such happy to engage in technical discussions. Furthermore, when stakeholders had questions or concerns, addressing them and implementing their suggestions resulted in them having more trust in the model and results. Finally, stakeholders readily engaged in brainstorming together when it came to model considerations, and

were very quick to jump in and provide insights from their own expertise.

What implementations perform best when scoring alternatives according to the stakeholder criteria, based on the model, stakeholder input, and literature? The best performing solutions overall, where the Basecase and Land Increase using a Pipeline. Even though the land raising case is quite a bit more expensive per cubic metre it can offset that by providing additional benefits that the basecase cannot.

Based on the experiences from the case study, what would a framework with participatory logistical modelling look like for dredge sediment re-use problems? Based on all observations and the modelling experience, the approach this research utilised worked quite well, and given that stakeholders expressed interests in continuing to work with the model and this method it seems they would agree. It may be beneficial, to ask for more input from the stakeholder especially when it comes to model parameters as they may have proprietary information that could improve the accuracy of the model, and the stakeholders trust in the model as well. Furthermore, it is important to consider that as the stakeholders in this case were part of an existing consortium they would have had an existing rapport. When considering a similar approach in a different setting or with more widely varied stakeholders it may be necessary to work on developing a rapport first, and re-establish the decision making criteria.

In conclusion logistical modelling does provide useful insights for facilitate decision making, by facilitating stakeholder discussion and providing a more tangible defined case to consider with quantitative values. However, future research could expand the involved stakeholders, the modelling accuracy, or explore how this method performs in other groups and other locals.

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Ethical Guidelines and Risk Management

In order to collect and process data from human participants considerations had to be made for the sensitivity of the data collected and its storage. Of key importance is that the collected data was anonymous and stored storage medium compliant with the TU Delft Human Research Ethics guidelines.



Model Input Parameters

The values in the table below were mostly estimated based on sources available through quick google searches, the main relevant sources are cited in the main text. The Pipeline costs are a very rough estimation based on sources of pipeline segment costs and some input of off-shore pipeline projects. The dredging vessel statistics are all from.

Table B.1: All input parameters used for model code

Variable	Value	Description
Fuel_consumption_Lhr	400	VLSFO consumption dredging vessels Liter per Hour
Fuel_consumption_GkWh	190	VLSFO consumption dredging vessels Grams per kWh
Fuel_consumption_LkWh	0.224	VLSFO consumption dredging vessels Liter per kWh
CO2Emission	2.68	VLSFO CO2 emissions
COEmission	0.5	VLSFO CO emissions
NOxEmission	60	VLSFO NOx emissions
SOxEmission	2.8	VLSFO SOx emissions
PMEmission	0.1	VLSFO PM emissions
Fuel_price_tonne	575	VLSFO price per tonne (1000 kg)
Fuel_density	900	VLSFO density kg/m3
Fuel_price_m3	517.5	VLSFO price per m3
Fuel_price_l	0.5175	VLSFO price per Liter
Diesel_power	9.94	energy content diesel fuel kWh per Liter
Diesel_efficiency	0.38	efficiency of diesel engines
Diesel_cost	1.65	price of diesel in euros per liter
Diesel_emissions_CO2	2.68	kg of CO2 per liter of diesel consumed
Digger_fuel_consumption	0.4	Fuel consumption of a digger per m3 of material moved
Digger_emissions_CO2	1.4	CO2 emissions of digger per m3 of material moved
Digger_fuel_time	16	Digger fuel consumed per hour of operations
Beunbak_fuel	0.1	Fuel consumption of beunbak per m3 of sediment
Beunbak_emissions_CO2	0.3	CO2 emissions of beunbak per m3 of sediment transported
Beunbak_capacity	1000	m3 capacity of beunbak convoi (estimated)
Kipper_fuel	0.5275	Fuel consumption of kipper per m3 of sediment per km
Kipper_emissions_CO2	0.29	CO2 emissions of beunbak per m3 of sediment transported per km
Kipper_capacity	18	m3 capacity of kipper (behind tractor)
Truck_fuel	0.028	Fuel consumption of truck per m3 of sediment per km
Truck_emissions_CO2	0.09	CO2 emissions of kipper per m3 of sediment transported per km
Truck_capacity	22	m3 capacity of sediment truck
Pipeline_distance	3	Distance of pipeline constructed
Pipeline_construction_cost	€ 1,500,000.00	Cost estimates of pipeline constructed per km
Pipeline_construction_emission	204,000.00	emissions of pipeline construction per km
Pipeline_operating_cost	€ 25,000.00	operating costs of the pipeline per km
Pipeline_crew	2	amount of crew needed to keep pipeline operational
Pipeline_salary	3000	salary for those crew
Pipeline_pump_power	3600	power of the pump connected to the pipeline for contiuity of sediment flow
Transport_distance	4.7	Driving distance depot to placement location
Trip_time	0.2	Driving time depot to placement location
Load_time	0.25	Time it takes to load the truck with sediment from the depot
Unload_time	0.2	Time it takes to unload the sediment at the placement local
Truck_speed	23.5	avg speed truck for route kmph
Kipper_speed	23.5	avg speed kipper for route kmph
Barge_speed	30	avg speed truck for route kmph
Digger_speed	88	m3/h a digger can transfer to transport vessel (rough est)
Truck_salary	2500	salary for truck driver
Truck_rental	95	rental cost driver including driver per h
Digger_rental	140	rental cost digger including operator per h
Barge_rental	200	est. Rental cost plus operator per h
Kipper_rental	95	est. Rental cost plus operator per h (assumed same as truck)
Transport_distance_conc	6.5	Driving distance drying location to concrete manufacturer
Crew_salary	3000	Average Salary of all dredging vessel crew in euro
Drying_time_pond	365	Drying time for a layer of 1m in days in a lagoon env
Drying_time_natural	90	Drying time for a layer of 1m in days with biota supported drying
Drying_time_External	6	Drying time
Volume_change	2	Factor of change in volume for drying sediment
Ripening_emissions	0.012	emissions in co2 from ripeing sediment
Soil_density	700	Density of dried sediment
Worm_concentration	0.1	concentration of worms in kg per m3 dredge sediment
Worm_price	2.25	purchase price of worms in euros per kg
Dredge_density	1200	Density of dredged sediment
Land_capacity	1200000	m2 of land available
Land_rent_price	1800	price in euro per year per 10000m2
Desired_layer_thickness	0.2	desired thickness of drying layer in meters
External_drying_capacity	2457	amount of m3 wet sediment external service can process per hour (mechanical drying)
External_service_costs	11097	cost of external sevice per operating hour
External_power_consumption	700	kWh
EMO_drying_capacity	819	amount of m3 wet sediment external service can process per hour (mechanical drying) 1 machine
EMO_service_costs	3391	cost of external sevice per operating hour
EMO_power_consumption	300	kWh
Ripening_emissions_pond	0	kgCO2 per m3 (from the oxidation of the dredge sediment)
Ripening_emissions_nature	0	kgCO2 per m3 (from the oxidation of the dredge sediment)
Ripening_emissions_external	0	kgCO2 per m3 (from the oxidation of the dredge sediment)
Ripening_emissions_basecase	0	kgCO2 per m3 (from the oxidation of the dredge sediment)
Ripening_emissions_land	0	kgCO2 per m3 (from the oxidation of the dredge sediment)
Electricity_emissions_NL	0.37	kgCO2 per kWh

Table B.2: Input parameters for several dredging vessels commonly used in the Port of Rotterdam area

Name	Capacity	Speed_Loaded	Speed_Unloaded	Power_Dredging	Power_Sailing	Power_Unloading	Fuel_consumption	Dredging_Time	Unloading_Time	Crew
Crestway	5600	13	13.5	6000	4000	2000	0.224	3600	600	14
Medway	7516	11.5	12	5400	3400	2000	0.224	3600	600	16
Gateway	12000	15.4	16	13000	12000	8000	0.224	7200	600	24
Strandway	4500	11	11.5	5000	2982	2000	0.224	3600	600	12
StrandwayLand	4500	11	11.5	5000	2982	5000	0.224	3600	3600	12



Model Results

Table C.1: Analysis results for contractor

Contractor	Cost	Emission	Time	Safety	Sustainability	Nature Value	Environmental Quality	Bureaucracy	Total
ranking	2	4	3	1	5	6	7	8	
weights	0.184	0.091984	0.1226	0.3679	0.073587385	0.061322821	0.052562418	0.045992116	
BaseNW	4.99	4.93	4.38	4	2	1	2	5	3.93
BaseMV	5.00	5.00	4.49	4	2	1	2	5	3.95
ConcNWPO	4.13	2.05	1.00	4	5	3.5	3	1	3.33
ConcNWES	1.09	1.92	1.00	4	5	3	3	2	2.77
ConcNWN	4.00	2.05	1.00	4	5	3.5	3	1	3.31
ConcMVPO	3.95	1.12	1.00	4	5	3.5	3	1	3.21
ConcMVES	0.98	1.00	1.00	4	5	3	3	2	2.67
ConcMVN	3.88	1.14	1.00	4	5	3.5	3	1	3.20
LandNWP	1.84	3.24	5.00	4	5	4	4	2	3.64
LandNWT	4.29	2.44	1.02	4	4	4	3	1	3.35
LandMVP	4.49	3.07	3.39	4	5	4	4	2	3.91
LandMVT	4.19	1.54	1.02	4	4	4	3	1	3.25

Table C.2: Analysis results for deltas

Deltares	Cost	Emission	Time	Safety	Sustainability	Nature Value	Environmental Quality	Bureaucracy	Total
ranking	2	4.5	5	4.5	2	4	7	7	
weights	0.229	0.101929	0.0917	0.1019	0.229341099	0.11467055	0.065526028	0.065526028	
BaseNW	4.99	4.93	4.38	4	2	1	2	5	3.49
BaseMV	5.00	5.00	4.49	4	2	1	2	5	3.51
ConcNWPO	4.13	2.05	1.00	4	5	3.5	3	1	3.47
ConcNWES	1.09	1.92	1.00	4	5	3	3	2	2.76
ConcNWN	4.00	2.05	1.00	4	5	3.5	3	1	3.44
ConcMVPO	3.95	1.12	1.00	4	5	3.5	3	1	3.33
ConcMVES	0.98	1.00	1.00	4	5	3	3	2	2.65
ConcMVN	3.88	1.14	1.00	4	5	3.5	3	1	3.31
LandNWP	1.84	3.24	5.00	4	5	4	4	2	3.62
LandNWT	4.29	2.44	1.02	4	4	4	3	1	3.37
LandMVP	4.49	3.07	3.39	4	5	4	4	2	4.06
LandMVT	4.19	1.54	1.02	4	4	4	3	1	3.26

Table C.3: Analysis results for dredgers

Dredger	Cost	Emission	Time	Safety	Sustainability	Nature Value	Environmental Quality	Bureaucracy	Total
ranking	4	4.5	5.5	2.25	4	3.5	4.75	7	
weights	0.126	0.111805	0.0915	0.2236	0.125780937	0.143749642	0.105920789	0.071874821	
BaseNW	4.99	4.93	4.38	4	2	1	2	5	3.44
BaseMV	5.00	5.00	4.49	4	2	1	2	5	3.46
ConcNWPO	4.13	2.05	1.00	4	5	3.5	3	1	3.26
ConcNWES	1.09	1.92	1.00	4	5	3	3	2	2.86
ConcNWN	4.00	2.05	1.00	4	5	3.5	3	1	3.24
ConcMVPO	3.95	1.12	1.00	4	5	3.5	3	1	3.13
ConcMVES	0.98	1.00	1.00	4	5	3	3	2	2.74
ConcMVN	3.88	1.14	1.00	4	5	3.5	3	1	3.12
LandNWP	1.84	3.24	5.00	4	5	4	4	2	3.72
LandNWT	4.29	2.44	1.02	4	4	4	3	1	3.27
LandMVP	4.49	3.07	3.39	4	5	4	4	2	3.88
LandMVT	4.19	1.54	1.02	4	4	4	3	1	3.15

Table C.4: Analysis results for PoR

PoR	Cost	Emission	Time	Safety	Sustainability	Nature Value	Environmental Quality	Bureaucracy	Total
ranking	2.833	4.33333	4.6667	2	3.33333	5	6.33333	7.5	
weights	0.169	0.110457	0.1026	0.2393	0.143593971	0.095729305	0.075575771	0.063819536	
BaseNW	4.99	4.93	4.38	4	2	1	2	5	3.65
BaseMV	5.00	5.00	4.49	4	2	1	2	5	3.67
ConcNWPO	4.13	2.05	1.00	4	5	3.5	3	1	3.33
ConcNWES	1.09	1.92	1.00	4	5	3	3	2	2.82
ConcNWN	4.00	2.05	1.00	4	5	3.5	3	1	3.31
ConcMVPO	3.95	1.12	1.00	4	5	3.5	3	1	3.19
ConcMVES	0.98	1.00	1.00	4	5	3	3	2	2.70
ConcMVN	3.88	1.14	1.00	4	5	3.5	3	1	3.18
LandNWP	1.84	3.24	5.00	4	5	4	4	2	3.67
LandNWT	4.29	2.44	1.02	4	4	4	3	1	3.30
LandMVP	4.49	3.07	3.39	4	5	4	4	2	3.93
LandMVT	4.19	1.54	1.02	4	4	4	3	1	3.19

Table C.5: Analysis results for RWS

RWS	Cost	Emission	Time	Safety	Sustainability	Nature Value	Environmental Quality	Bureaucracy	Total
ranking	3.667	4.33333	4.3333	3.3333	4.666666667	5.333333333	5.333333333	5	
weights	0.15	0.126549	0.1265	0.1645	0.117510091	0.102821329	0.102821329	0.109676085	
BaseNW	4.99	4.93	4.38	4	2	1	2	5	3.68
BaseMV	5.00	5.00	4.49	4	2	1	2	5	3.70
ConcNWPO	4.13	2.05	1.00	4	5	3.5	3	1	3.03
ConcNWES	1.09	1.92	1.00	4	5	3	3	2	2.62
ConcNWN	4.00	2.05	1.00	4	5	3.5	3	1	3.01
ConcMVPO	3.95	1.12	1.00	4	5	3.5	3	1	2.88
ConcMVES	0.98	1.00	1.00	4	5	3	3	2	2.48
ConcMVN	3.88	1.14	1.00	4	5	3.5	3	1	2.87
LandNWP	1.84	3.24	5.00	4	5	4	4	2	3.61
LandNWT	4.29	2.44	1.02	4	4	4	3	1	3.04
LandMVP	4.49	3.07	3.39	4	5	4	4	2	3.78
LandMVT	4.19	1.54	1.02	4	4	4	3	1	2.91



Scoring Matrices

Maasvlakte Base Case Placement at Sea 1 lowest 5 highest

Criteria	Rank	Score [1-5]	Reasoning
2.5625	Safety	4	Pfas was ignored very long otherwise safe and necessary
3.1250	Costs	5	Model Scoring
3.6875	Sustainability	3	Damaging to marine eco system, feeding the global sediment system, elevated emissions
4.5000	Emissions	5	Model Scoring
4.6250	Nature Value	3	The placement of sediment is important for feeding the coastal sediment flows and maintaining the waddenze. Placement however does negatively impact the local environment destroying bentic life in the placement site.
4.7500	Time	4	Model Scoring
5.8750	Environmental Quality (inc. Aesthetic)	2	The environmental impact is limited beyond what is captured in the nature value. There is no real aesthtic impact and no local inhabitants that would complain, it does as such also not contribute possitively in any way.
6.8750	Bureaucratic difficulties	5	Base case bureacracy already settled

Figure D.1: Maasvlakte BaseCase

Nieuwe Waterweg Base Case Placement at Sea 1 lowest 5 highest

Criteria	Rank	Score [1-5]	Reasoning
2.5625	Safety	4	Pfas was ignored very long otherwise safe and necessary
3.1250	Costs	5	Model Scoring
3.6875	Sustainability	3	Damaging to marine eco system, feeding the global sediment system, elevated emissions
4.5000	Emissions	5	Model Scoring
4.6250	Nature Value	3	The placement of sediment is important for feeding the coastal sediment flows and maintaining the waddenze. Placement however does negatively impact the local environment destroying bentic life in the placement site.
4.7500	Time	4	Model Scoring
5.8750	Environmental Quality (inc. Aesthetic)	2	The environmental impact is limited beyond what is captured in the nature value. There is no real aesthetic impact and no local inhabitants that would complain, it does as such also not contribute positively in any way.
6.8750	Bureaucratic difficulties	5	Base case bureaucracy already settled

Figure D.2: Nieuwe Waterweg BaseCase

Maasvlakte Case: Concrete production Pond

Criteria	Rank	Score [1-5]	Reasoning
2.5625	Safety	4	Clean sediment, acceptable pollution levels shift over time
3.1250	Costs	4	Model Scoring
3.6875	Sustainability	5	Reduce necessary imports, reuse of waste material, implemented in the right way completely recyclable
4.5000	Emissions	1	Model Scoring
4.6250	Nature Value	3.5	Potential to create reefy style blocks, slightly better than basecase
4.7500	Time	1	Model Scoring
5.8750	Environmental Quality (inc. Aesthetic)	3	Not very interesting, not polluting but no aesthetic added values. Added marketability due to recycled materials, the drying pond may be considered unattractive by local inhabitants
6.8750	Bureaucratic difficulties	1	Approval needed for new concrete materials, also material may require to be redesignated as base material not waste material, concrete manufacturer needs to be on board

Figure D.3: Maasvlakte Concrete Pond

Maasvlakte Case: Concrete production Natural

Criteria	Rank	Score [1-5]	Reasoning
2.5625	Safety	4	Clean sediment, acceptable pollution levels shift over time
3.1250	Costs	4	Model Scoring
3.6875	Sustainability	5	Reduce necessary imports, reuse of waste material
4.5000	Emissions	1	Model Scoring
4.6250	Nature Value	3.5	Potential to create reefy style blocks, slightly better than basecase
4.7500	Time	1	Model Scoring
5.8750	Environmental Quality (inc. Aesthetic)	3	Not very interesting, not polluting but no aesthetic added values. Added marketability due to recycled materials
6.8750	Bureaucratic difficulties	1	Approval needed for new concrete materials, also material may require to be redesignated as base material not waste material, concrete manufacturer needs to be on board

Figure D.4: Maasvlakte Concrete Nature

Maasvlakte Case: Concrete production External

Criteria	Rank	Score [1-5]	Reasoning
2.5625	Safety	4	Clean sediment, acceptable pollution levels shift over time
3.1250	Costs	1	Model Scoring
3.6875	Sustainability	5	Reduce necessary imports, reuse of waste material
4.5000	Emissions	1	Model Scoring
4.6250	Nature Value	3.5	Potential to create reefy style blocks, slightly better than basecase
4.7500	Time	1	Model Scoring
5.8750	Environmental Quality (inc. Aesthetic)	3	Not very interesting, not polluting but no aesthetic added values. Added marketability due to recycled materials
6.8750	Bureaucratic difficulties	1	Approval needed for new concrete materials, also material may require to be redesignated as base material not waste material, concrete manufacturer needs to be on board

Figure D.5: Maasvlakte Concrete External

Nieuwe Waterweg Case: Concrete production Pond

Criteria	Rank	Score [1-5]	Reasoning
2.5625	Safety	4	Clean sediment, acceptable pollution levels shift over time
3.1250	Costs	4	Model Scoring
3.6875	Sustainability	5	Reduce necessary imports, reuse of waste material
4.5000	Emissions	1	Model Scoring
4.6250	Nature Value	3.5	Potential to create reefy style blocks, slightly better than basecase
4.7500	Time	1	Model Scoring
5.8750	Environmental Quality (inc. Aesthetic)	3	Not very interesting, not polluting but no aesthetic added values. Added marketability due to recycled materials
6.8750	Bureaucratic difficulties	1	Approval needed for new concrete materials, also material may require to be redesignated as base material not waste material, concrete manufacturer needs to be on board

Figure D.6: Nieuwe Waterweg Concrete Pond

Nieuwe Waterweg Case: Concrete production Natural

Criteria	Rank	Score [1-5]	Reasoning
2.5625	Safety	4	Clean sediment, acceptable pollution levels shift over time
3.1250	Costs	4	Model Scoring
3.6875	Sustainability	5	Reduce necessary imports, reuse of waste material
4.5000	Emissions	1	Model Scoring
4.6250	Nature Value	3.5	Potential to create reefy style blocks, slightly better than basecase
4.7500	Time	1	Model Scoring
5.8750	Environmental Quality (inc. Aesthetic)	3	Not very interesting, not polluting but no aesthetic added values. Added marketability due to recycled materials
6.8750	Bureaucratic difficulties	1	Approval needed for new concrete materials, also material may require to be redesignated as base material not waste material, concrete manufacturer needs to be on board

Figure D.7: Nieuwe Waterweg Concrete Nature

Nieuwe Waterweg Case: Concrete production External

Criteria	Rank	Score [1-5]	Reasoning
2.5625	Safety	4	Clean sediment, acceptable pollution levels shift over time
3.1250	Costs	1	Model Scoring
3.6875	Sustainability	5	Reduce necessary imports, reuse of waste material
4.5000	Emissions	1	Model Scoring
4.6250	Nature Value	3.5	Potential to create reefy style blocks, slightly better than basecase
4.7500	Time	1	Model Scoring
5.8750	Environmental Quality (inc. Aesthetic)	3	Not very interesting, not polluting but no aesthetic added values. Added marketability due to recycled materials
6.8750	Bureaucratic difficulties	1	Approval needed for new concrete materials, also material may require to be redesignated as base material not waste material, concrete manufacturer needs to be on board

Figure D.8: Nieuwe Waterweg Concrete External

Maasvlakte Case: Land raising Pipeline

Criteria	Rank	Score [1-5]	Reasoning
2.5625	Safety	4	Sediment rated "Altijd toebasbaar", land may be safer from floods in future, complexity in maintaining safe implementation
3.1250	Costs	4	Model Scoring
3.6875	Sustainability	5	Placing sediment where original river delta might have placed it, capturing carbon
4.5000	Emissions	4	Model Scoring
4.6250	Nature Value	4	Providing new soil to agriculturally depleted land,
4.7500	Time	3	Model Scoring
5.8750	Environmental Quality (inc. Aesthetic)	4	Implementation won't be pretty during drying, becomes potentially natural area (repurposing), otherwise continued farmland
6.8750	Bureaucratic difficulties	1	Convince farmers, clearing by relevant state bodies, potentially need land rezoning, sediment classification

Figure D.9: Maasvlakte Land Pipeline

Maasvlakte Case: Land raising Trucks

Criteria	Rank	Score [1-5]	Reasoning
2.5625	Safety	4	Sediment rated "Altijd toebasbaar", land may be safer from floods in future, complexity in maintaining safe implementation
3.1250	Costs	4	Model Scoring
3.6875	Sustainability	5	Placing sediment where original river delta might have placed it, capturing carbon
4.5000	Emissions	4	Model Scoring
4.6250	Nature Value	4	Providing new soil to agriculturally depleted land,
4.7500	Time	1	Model Scoring
5.8750	Environmental Quality (inc. Aesthetic)	4	Implementation won't be pretty during drying, becomes potentially natural area (repurposing), otherwise continued farmland
6.8750	Bureaucratic difficulties	1	Convince farmers, clearing by relevant state bodies, potentially need land rezoning, sediment classification

Figure D.10: Maasvlakte Land Trucks

Nieuwe Waterweg Case: Land raising Pipeline

Criteria	Rank	Score [1-5]	Reasoning
2.5625	Safety	4	Sediment rated "Altijd toebasbaar", land may be safer from floods in future, complexity in maintaining safe implementation
3.1250	Costs	2	Model Scoring
3.6875	Sustainability	5	Placing sediment where original river delta might have placed it, capturing carbon
4.5000	Emissions	5	Model Scoring
4.6250	Nature Value	4	Providing new soil to agriculturally depleted land,
4.7500	Time	5	Model Scoring
5.8750	Environmental Quality (inc. Aesthetic)	4	Implementation won't be pretty during drying, becomes potentially natural area (repurposing), otherwise continued farmland
6.8750	Bureaucratic difficulties	1	Convince farmers, clearing by relevant state bodies, potentially need land rezoning, sediment classification

Figure D.11: Nieuwe Waterweg Land Pipeline

Nieuwe Waterweg Case: Land raising Trucks

Criteria	Rank	Score [1-5]	Reasoning
2.5625	Safety	4	Sediment rated "Altijd toebasbaar", land may be safer from floods in future, complexity in mainatining safe implementation
3.1250	Costs	4	Model Scoring
3.6875	Sustainability	5	Placing sediment where original river delta might have placed it, capturing carbon
4.5000	Emissions	4	Model Scoring
4.6250	Nature Value	4	Providing new soil to agriculturally depleted land,
4.7500	Time	1	Model Scoring
5.8750	Environmental Quality (inc. Aesthetic)	4	Implementation won't be pretty during drying, becomes potentially natural area (repurposing), otherwise continued farmland
6.8750	Bureaucratic difficulties	1	Convince farmers, clearing by relevant state bodies, potentially need land rezoning, sediment classification

Figure D.12: Nieuwe Waterweg Land Trucks



Stakeholder Input

The survey of stakeholder opinions contained the following questions.

- What organisation do you represent/work for?
- How would you rank the following aspects of Dredge Sediment management options in order of importance?
 - Safety;Sustainability;Costs;Emissions;Nature Value;Time;Environmental Quality (inc. Aesthetic);Bureaucratic difficulties
- In case you feel any criteria were missing add them here
- How likely do you view the implementation of a Wisselpolder as alternative sediment management?
- What would you say is the biggest obstacle in implementing a Wisselpolder?
- Has your opinion on the likelihood of implementation changed based on the provided information?
- Is there anything particular about the information or process that led to this change?
- Would you be willing to participate in a workshop in the coming month further assessing this method for decision making facilitation?



Dredging the Future

Assessing the Impact of Alternative Uses of
Dredge Sediment in the Port of Rotterdam

Floris van der Heijde, MSc Engineering and Policy Analysis

