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Maintenance Dredging in Ports and Waterways

A framework for making smart, sustainable, and circular strategies quantifiable



Arash Sepehri

MAINTENANCE DREDGING IN PORTS AND WATERWAYS

**A FRAMEWORK FOR MAKING SMART, SUSTAINABLE, AND CIRCULAR STRATEGIES
QUANTIFIABLE**

MAINTENANCE DREDGING IN PORTS AND WATERWAYS

**A FRAMEWORK FOR MAKING SMART, SUSTAINABLE, AND CIRCULAR STRATEGIES
QUANTIFIABLE**

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CONTENTS

Summary	vii
Preface	ix
1. Introduction	1
1.1. Research context	1
1.2. Problem statement	9
1.3. Research gap	9
1.4. Research objective	9
1.5. Research questions	10
1.6. Research outlines	10
2. Literature Review	11
2.1. Introduction	12
2.2. Method	13
2.3. Results	15
2.4. Discussion	26
2.5. Conclusion	28
3. Smart Port Maintenance	31
3.1. Introduction	32
3.2. Method	33
3.3. Results	33
3.4. Discussion	37
3.5. Conclusion	38
4. Sustainable Port Maintenance	41
4.1. Introduction	42
4.2. Method	43
4.3. Results	47
4.4. Discussion	51
4.5. Conclusion	53
5. Circular Port Maintenance	55
5.1. Introduction	56
5.2. Methods	57
5.3. Results	62
5.4. Discussion	68
5.5. Conclusion	69
6. Discussion	71
6.1. Reflection on research methods and underlying assumptions	71
6.2. Reflective positioning and main contributions	73
6.3. Implications	74
7. Conclusions and Recommendations	77
7.1. Reflection on problem statement and research objective	77
7.2. Answering research questions	77
7.3. Recommendations for future research	79
7.4. Final reflection	81

A. Appendix A	99
A.1. Propulsion power	100
A.2. Pump power	107
B. Appendix B	111
B.1. Total loading and unloading duration of a TSHD	111
B.2. Total dredging duration of a WID	116
Acknowledgments	119
List of Publications	121

SUMMARY

The ability of ports to guarantee continuous nautical accessibility is essential for safeguarding supply chain reliability and maintaining a competitive position. Yet this accessibility is persistently challenged by natural sedimentation processes that reduce navigable depth, cause operational delays, and require recurrent maintenance dredging. Traditionally, the selection of maintenance strategies has focused on optimizing time and cost. However, society, regulators, and industry increasingly demand that port maintenance also contributes to digitalization, environmental performance, and circular resource use. Although these value dimensions (smartness, sustainability, and circularity) are now widely invoked, they remain insufficiently tangible for use in operational decision-making. Existing literature offers conceptual descriptions, but rarely provides quantitative indicators, benchmarks, or decision procedures that stakeholders can apply in practice.

This dissertation addresses this gap by developing a framework that translates smartness, sustainability, and circularity into measurable and comparable indicators. Using a Systematic Literature Review (SLR) combined with the Frame of Reference (FoR), the research shows that although stakeholders, particularly port authorities and contractors, often share similar strategic objectives, their perspectives diverge at the operational level, leading to differences in indicators, benchmarks, and decision recipes. While previous studies mainly highlighted these contrasts conceptually, this dissertation advances the field by operationalizing them into practical, quantitative tools that better reflect the realities of port maintenance projects and help bridge these gaps in decision-making.

Building on these insights, the dissertation develops three dedicated methodological instances, one for each value dimension, that extend the frame of reference analysis into operational and quantifiable form. These instances are constructed to accommodate the distinct perspectives of port authorities and contractors, ensuring that indicators can be interpreted and applied to real-world cases. Across all three, a unifying feature is the structuring of operational processes into event tables, enabling comparisons at multiple levels: large-scale patterns, intermediate processes, and phase-specific drivers. This approach, not previously applied in the port maintenance domain, provides transparency, modularity, and analytical depth.

For smart port maintenance, Automatic Identification System (AIS) logs of seagoing vessels and dredging vessels are collected, processed, and analyzed to quantify how maintenance dredging interacts with seagoing navigation processes. By linking dredger trajectories with port traffic patterns, the study identifies spatial and temporal interference zones and uncovers cascading effects on accessibility. Rather than optimizing operations directly, the method demonstrates how data-driven analyses can reveal opportunities for improving planning and reducing navigational disruptions, something that was difficult to quantify with existing tools.

For sustainable port maintenance, a physics-based and discrete-event simulation model is developed to quantify energy footprint and carbon emissions for two types of dredging vessels under varying operational conditions. The model integrates sediment characteristics, hydrodynamics, vessel power requirements, and, beyond conventional sailing resistance, explicitly incorporates the resistance components of dredging equipment such as dragheads, jet systems, and pumps. The dredging process is subdivided into discrete phases and represented in an event table, allowing transparent attribution of emissions to specific operational steps. The method clarifies the functional relationship between project duration and emissions, and provides a structured quantitative basis for stakeholders to evaluate alternative strategies, capabilities that were previously scattered across disparate models and difficult to compare.

For circular port maintenance, two indicators are introduced to quantify sediment reusability and retention, enabling the comparison of fundamentally different maintenance strategies. A key contribution is the explicit identification of circularity boundaries in space and time: value from sediment reuse may arise outside the port system and on much longer timescales than the dredging operations that supply the material. These boundaries were conceptually recognized in the literature but had not been formalized or quantified. By comparing a conventional linear reallocation scenario with a dike reinforcement reuse scenario, the study shows how circularity influences energy use, emissions, and material flows, while illustrating how the event table approach helps relate long-term value creation to short-term dredging activities. Again, the objective is not to perform a complete trade-off, but to create the quantitative foundation on which such trade-offs could be constructed.

Across these three dimensions, the dissertation contributes to the scientific and practical discourse in several ways. First, it clarifies and operationalizes emerging value dimensions, smartness, sustainability, and circularity, which are increasingly relevant but poorly defined in current practice. Second, it demonstrates how multi-level event tables can be used to structure and compare operational processes in a transparent and reproducible way. Third, it provides quantitative indicators and analytical methods that allow future decision-support tools to incorporate environmental, digital, and circularity considerations alongside traditional cost–time analyses. Finally, the research shows how stakeholder perspectives can be embedded into methodological design, ensuring that indicators reflect real-world needs rather than abstract ideals.

In conclusion, this dissertation provides a methodological foundation for systematically incorporating smartness, sustainability, and circularity into maintenance dredging decisions. By operationalizing these value dimensions into measurable indicators and integrating stakeholder perspectives within event-based analytical frameworks, the research advances current practice beyond predominantly time–cost considerations. The proposed methods enhance transparency, support more structured dialogue between port authorities and contractors, and create the conditions for future development of integrated, multi-objective decision-support systems. In doing so, this work contributes to the scientific discourse on port maintenance while offering practically applicable tools that can inform more robust, environmentally responsible, and future-oriented sediment management strategies.

PREFACE

With the continued growth of global demand for goods, maritime transport has become more essential than ever, placing increasing pressure on ports to operate efficiently, reliably, and sustainably. Shipping companies are investing in ever larger vessels to benefit from economies of scale, which in turn requires ports to accommodate deeper drafts, higher traffic volumes, and stricter operational constraints. These developments place unprecedented demands on port infrastructure and make regular maintenance dredging indispensable to safeguard nautical accessibility, avoid operational disruptions, and maintain the competitiveness of ports within regional and global networks.

This dissertation is motivated by the observation that, while maintenance dredging is fundamental to port performance, decisions surrounding it have traditionally been dominated by cost and time considerations. At the same time, ports and dredging contractors are increasingly confronted with societal, environmental, and regulatory expectations that call for smarter use of data, lower environmental impacts, and more circular use of resources. Although concepts such as smartness, sustainability, and circularity are now widely referenced in policy documents and strategic visions, they often remain insufficiently defined and difficult to translate into operational decision-making. This tension between growing ambitions and limited practical tools formed the starting point of this research.

The work presented in this dissertation aims to contribute to bridging this gap by developing structured, quantitative approaches that make these emerging value dimensions more tangible and comparable in the context of port maintenance dredging. By combining conceptual frameworks with data-driven and physics-based methods, the research seeks to support more transparent discussions between port authorities and dredging contractors, grounded in operational realities rather than abstract aspirations.

This research was conducted in close collaboration with Van Oord Dredging and Marine Contractors, which provided valuable opportunities to connect academic inquiry with real-world practice. Access to operational data, case studies, and industry expertise allowed the research to be continuously tested against practical constraints and decision-making contexts. This combination of academic rigor and practical relevance shaped both the direction of the research and its methodological choices.

Beyond its technical contributions, this dissertation reflects my personal journey as a researcher navigating the interface between engineering, decision-making, and societal values. The PhD process has challenged me to think critically about not only how systems function, but also how choices are made within them, and which values are implicitly prioritized. I hope that the methods and insights presented in this work contribute, in a modest but meaningful way, to more informed and balanced decision-making in port maintenance and beyond.

*Arash Sepehri
Delft, December 2025*

1

INTRODUCTION

1.1. RESEARCH CONTEXT

Global waterborne trade continues to grow, creating increasing pressure on ports to efficiently accommodate larger vessels and higher cargo volumes (S. E. Hanson and Nicholls, 2020). The efficiency and reliability of port operations are central to the performance of international supply chains. The quality of port and waterway infrastructure influences vessel waiting times, service levels, and the competitive positioning of ports within global transport networks (Wagner *et al.*, 2022). To sustain these functions, port authorities worldwide invest extensively in both infrastructure development and maintenance strategies aimed at ensuring safe, reliable, and efficient navigation (UNCTAD, 2023).

Ports and waterways operate as dynamic socio-technical systems in which hydrodynamic processes, sediment transport, infrastructure, and human interventions interact. Within this system, port accessibility is shaped by a combination of physical, operational, and institutional factors. These include water depth, channel layout, tidal windows, availability of pilots and tugs, and the capacity of traffic management services. Collectively, these elements determine not only navigational safety but also the operational reliability and throughput capacity of a port (Van Koningsveld *et al.*, 2023).

Sedimentation in navigation channels and berths poses one of the most persistent threats to port accessibility. Excessive or rapidly evolving sedimentation can reduce available water depth, restrict access windows, and cause vessel delays, leading to economic and competitiveness losses for port authorities (Guarnieri *et al.*, 2021). Maintenance dredging and associated mitigation measures; therefore, remain essential components of port management, as they ensure that natural morphodynamic processes do not compromise navigable depth or service levels (Sepehri *et al.*, 2024b; Issa-Zadeh and Garay-Rondero, 2025).

Managing these challenges requires coordination among a wide range of stakeholders, including port authorities, terminal operators, pilots, shipping companies, dredging contractors, environmental regulators, local communities, and governmental agencies. Each stakeholder affects (or is affected by) decisions related to accessibility, navigational safety, and sediment management. However, when focusing specifically on the realization of maintenance dredging projects, port authorities and dredging contractors emerge as the primary stakeholders, as they are directly responsible for planning, commissioning, and executing dredging activities. Other stakeholders may impose constraints or raise concerns about environmental impact, navigational downtime, or operational disruptions, yet the operational and decision-making core of maintenance dredging lies predominantly between the port authority and the contractor (Sepehri *et al.*, 2024a).

To support safe and efficient vessel access, port authorities rely heavily on continuous monitoring of hydrodynamic and morphodynamic conditions. Hydrographic surveys, including bathymetric measurements, current profiling, and water level observations, provide essential information on seabed evolution, sediment transport, and temporal variability in water depth. These datasets enable port authorities to evaluate deviations from desired boundaries, identify critical shoaling areas, and assess how natural fluctuations interact with operational constraints such as tidal windows or traffic demand. Survey data thus form the empirical foundation for determining when and where maintenance dredging should be performed, and to ensure that both safety criteria and service levels are maintained (EL-Hattab, 2014).

In practice, maintenance dredging has traditionally been organized around operational efficiency, with decision-making dominated by time and cost considerations. Port authorities aim to minimize navigational downtime and complete campaigns within strict operational windows, while contractors focus on achieving required bed levels with an agreed contract time frame (Sepehri *et al.*, 2024a). However, recent developments in environmental policy and circular resource management are now expanding the decision-making landscape.

New value dimensions, such as emissions, ecological impact, and opportunities for beneficial reuse of dredged sediments, are becoming increasingly relevant for port governance.

Despite their growing importance at strategic and policy levels, these considerations are not fully embedded in the operational tools, models, or contracting mechanisms used to plan and execute maintenance dredging (Laboyrie *et al.*, 2018). This emerging discrepancy reveals a gap between evolving societal and environmental ambitions and the practical decision frameworks currently employed by port authorities and contractors. Bridging this gap requires approaches that extend beyond traditional optimization-based on time and cost, to systematically integrate smartness, environmental, and circularity metrics into maintenance dredging decisions in operationally meaningful ways.

1.1.1. PORT ACCESSIBILITY

Port accessibility is not just a technical challenge; it plays a fundamental role in global supply chains and in how ports compete strategically. From a logistical perspective, a port that is more reliably accessible can reduce delays in vessel turnaround times, improving service levels for shipping lines and shippers. This matters both for just-in-time supply chains and for large-scale maritime trade. Competition between ports is increasingly shaped by accessibility. Large hub ports may compete on deep draft infrastructure and economies of scale, while smaller regional or feeder ports struggle to maintain draft or invest in deepening, but may differentiate through reliability or hinterland connections (Notteboom *et al.*, 2022).

Given its importance, it is useful to unpack exactly what port accessibility means in more detail. While a simplistic definition focuses on water depth, the reality is much more complex. Accessibility is determined by the interplay between hydrodynamic conditions, vessel characteristics, and bed level (PIANC, 2014). Besides, accessibility regulations such as draft restrictions, tidal windows, and navigational safety rules influence how often and how easily vessels can access a port. In addition, the availability and coordination of pilots, tugs, and vessel traffic services play a crucial role in minimizing waiting times and ensuring navigational safety. Recent studies show that waiting times, congestion, and priority rules have significant cascading effects on port accessibility (Nikghadam, 2023; Bakker *et al.*, 2024).

Another layer of nuance comes from differences between small and large ports. Ports with smaller infrastructure often lack the resources, traffic volumes, or operational requirements to justify deep channel maintenance or access for large vessels, so their accessibility strategies tend to focus on meeting local or regional needs (Medina *et al.*, 2007). In contrast, major commercial ports serving global liner shipping face stronger pressure to accommodate very large vessels and maintain high throughput, which demands more substantial dredging, infrastructure development, and operational coordination (Van Koningsveld *et al.*, 2007). Studies comparing navigation requirements across port sizes show that small ports typically prioritize basic access and low-cost maintenance, whereas large ports invest heavily in channel deepening, berth expansion, and more complex traffic management systems (Son *et al.*, 2020).

These differences in accessibility requirements across ports also shape the type and scale of dredging that is needed. In broad terms, capital dredging refers to the one-off or infrequent deepening and widening of channels, basins, and access routes to create new navigational capacity, typically required in large or expanding ports seeking to accommodate deeper draft vessels or new terminal layouts. By contrast, maintenance dredging involves the recurring removal of sediments that naturally re-accumulate due to hydrodynamic and morphological processes, ensuring that the port continues to meet its designated operational depth. Whereas capital dredging is driven by long-term infrastructure development and competitiveness goals, maintenance dredging is essential to preserve day-to-day accessibility and prevent draft restrictions (Sepehri *et al.*, 2024a).

Port accessibility depends on the relationship between vessel requirements and the navigable water column, as illustrated in Figure 1.1. The required water depth consists of the vessel's static draught plus allowances for squat, vertical motions, and an operational safety margin. The available water depth is determined by the Maintained Bed Level (MBL), the dredged depth, and the actual water level. The latter fluctuates due to tides, meteorological set-down, and waves, all depicted on the right side of the schematic. To ensure safe passage, ports apply a Under Keel Clearance (UKC), represented in the figure as the buffer between the keel and the MBL. This clearance accounts for squat (sinkage and trim) and for the vessel's vertical motions induced by waves and hydrodynamic effects. Over time, sedimentation raises the seabed above the maintained level, reducing this vertical margin and eventually triggering new dredging to restore the required water depth.

Accessibility is influenced not only by vertical constraints but also by horizontal tidal windows, during which tidal currents are low enough to permit safe maneuvering. Even when sufficient UKC exists, strong cross-currents can limit controllability, meaning a channel may be “deep enough” yet still inaccessible. As highlighted by Bakker *et al.* (2024), these horizontal constraints must be assessed together with depth

requirements when defining transit windows and planning maintenance dredging. The interaction between vessel motions, water level variations, sedimentation, and current conditions ultimately determines when vessels can safely transit, underscoring the need for continuous monitoring to support timely and efficient maintenance dredging operations (PIANC, 2014; Bakker *et al.*, 2024).

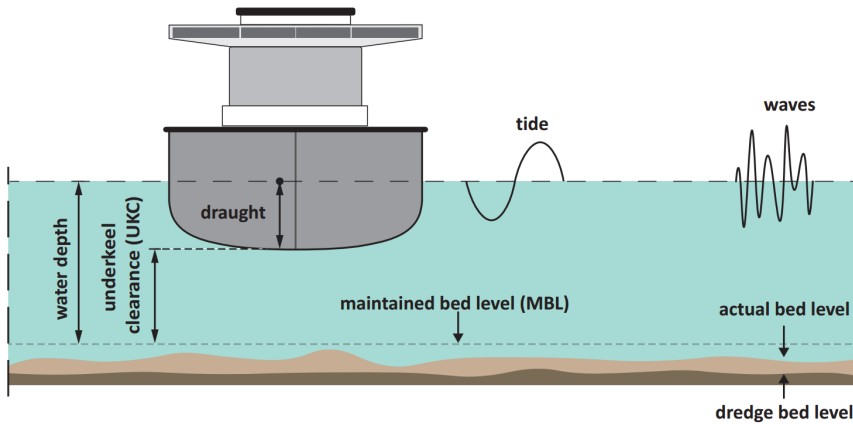


Figure 1.1.1: Water depth determined by hydrodynamic conditions, vessel characteristics, and bed level ensuring safe accessibility (modified from Van Koningsveld *et al.*, 2023).

Tidal windows alone rarely ensure sufficient access for modern deep draft vessels. Deepening channels can extend tidal availability but accelerate sedimentation and increase dredging needs, while shallower channels reduce dredging at the cost of accessibility. The optimal balance depends on local hydrodynamics, vessel traffic, and economic priorities, yet maintenance dredging remains unavoidable (Wan *et al.*, 2018). Consistent access also requires effective operational management. Ports must minimize downtime, avoid tidal delays, and prevent congestion in services such as pilotage, towage, and terminal operations. Continuous monitoring of hydrodynamic and morphodynamic conditions, through bathymetry, current profiling, and water level observations, provides critical insight into bed evolution, sediment deposition, and depth variability, enabling identification of shoaling hotspots and evaluation of navigational risks.

Hydrographic survey bathymetry data guide when and where dredging is needed. It indicates conditions that could restrict access, result in waiting times, or strain port services. Authorities set safety thresholds, while contractors execute operations accordingly. By linking bathymetry data with vessel characteristics and tidal constraints, ports define optimal dredge criteria and target bed levels to ensure adequate UKC. This data-driven approach enables adaptive dredging, reduces unnecessary sediment removal, and supports reliable, long-term port maintenance.

1.1.2. PORT MAINTENANCE STRATEGIES

Sedimentation directly affects navigable depth, making dredging essential for port accessibility. Without regular maintenance, ports risk reduced draft, operational restrictions, and exclusion of larger vessels. Given the recurring scale of maintenance dredging, small improvements in efficiency or decision-making, such as timing and location, can yield substantial cost savings, lower environmental impacts, and more predictable access for shipping lines.

Dredging methods are broadly classified as mechanical or hydraulic. Mechanical dredging excavates and removes consolidated sediment for transport to reallocation, permanent storage, or treatment sites. Hydraulic dredging, in contrast, suspends sediment in a water slurry or density current via suction or jetting, enabling its reallocation or re-mobilization within the aquatic system (Laboyrie *et al.*, 2018). Hydraulic methods are generally favored for large-scale transport of loosely packed sediments typical of maintenance dredging, while mechanical techniques are used for precision tasks in confined areas. Building on this distinction, Bianchini *et al.* (2019) and Sepehri *et al.* (2024a) identify three primary maintenance strategies: sediment reallocation, sediment re-mobilization, and mitigation measures.

A complementary approach is the PIANC's nautical bottom method, which increases effective nautical depth by allowing vessels to operate in controlled low-density and low-strength mud layers (PIANC, 2014; Kirichek *et al.*, 2018a). Though not a dredging method, additional water depth is achieved by defining the nautical bottom using density or yield stress criteria (Kirichek *et al.*, 2020; Ohle *et al.*, 2024). Figure 1.2 summarizes the classification of maintenance strategies used in this study. Each strategy involves specialized equipment and operational techniques tailored to sediment management needs. Port authorities focus on policy, monitoring, and safety, while contractors handle execution, equipment operation, and optimization. Effective port maintenance often requires combining strategies based on project specifications, sediment characteristics, and operational constraints.

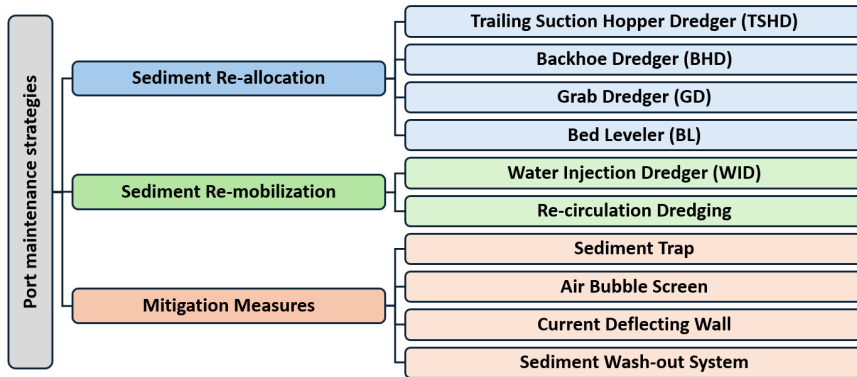


Figure 1.2.: Maintenance dredging strategies (modified from Sepehri *et al.*, 2024a).

SEDIMENT REALLOCATION

Sediment reallocation is a dredging approach in which sediments are physically collected, transported, and placed at designated deposition areas within the same system. An exception applies to contaminated sediments, which are dredged and placed in depots intended for permanent storage (Kirichek *et al.*, 2018b). Four main types of dredging equipment are commonly used for sediment reallocation: Trailing Suction Hopper Dredger (TSHD), Grab Dredger (GD), Back Hoe Dredger (BHD), and Bed Leveler (BL) (Laboyrie *et al.*, 2018; Sepehri *et al.*, 2024a).

TSHDs are mobile hydraulic dredgers equipped with dragheads and suction pipes that collect sediment while sailing slowly over the seabed. The material is stored in the vessel's hopper and transported to the placement area. Depending on project needs, TSHDs discharge sediment via bottom-door placement, rainbowing, or pipeline pumping (Ban and Bebić, 2023). Figure 1.3a illustrates a simplified TSHD cycle using bottom-door reallocation.

GDs are mechanical dredgers mounted on pontoons and equipped with a grab or clamshell bucket. The bucket digs into the sediment, closes, and is lifted to the surface by a wire-operated crane, making GDs suitable for precise dredging in confined areas (Figure 1.3c).

BHDs also operate from pontoons but use a hydraulic excavator arm with a bucket to dig and lift seabed sediments. Although they can be repositioned across the site, excavation is limited to a fixed reach, making BHDs effective for targeted dredging near quay walls or structures (Figure 1.3b). Sediments collected by GDs and BHDs are typically transferred to barges for transport to the reallocation site (C. Xu *et al.*, 2022).

While TSHDs are efficient along open, linear trajectories, they have limited accessibility near quay walls or corners. Mechanical dredgers (GDs and BHDs) perform better in confined spaces and therefore complement hydraulic dredgers. Finally, BLs (ploughs) are used to smooth the seabed after dredging by dragging a heavy blade to eliminate peaks and troughs and redistribute sediment over short distances, such as areas away from quay walls where the sediment can subsequently be collected by a TSHD (O'Brien, 2015) (Figure 1.3d). As each dredger type has distinct strengths, sediment reallocation typically relies on a tailored combination of equipment matched to the project's operational and spatial requirements.

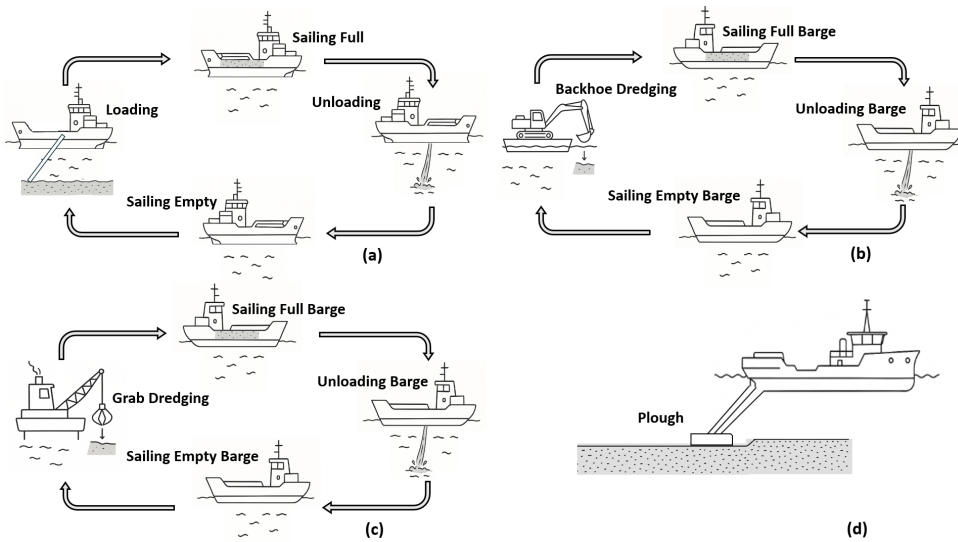


Figure 1.3.: Maintenance dredging with sediment reallocation using (a) TSHD, (b) BHD, (c) GD, and (d) BL.

SEDIMENT RE-MOBILIZATION

Sediment re-mobilization is the process by which deposited or consolidated fine-grained bed sediment is re-suspended, fluidized, or loosened by dredging activities and re-entrained into motion, forming a sediment plume in the water column, a density current, or fluid mud layer along the bed without being removed from the system. The magnitude and duration of re-mobilization depend on sediment characteristics, local hydrodynamics, and bed topography.

A Water Injection Dredger (WID) is a dredging vessel designed to maintain navigable depths without extracting sediment from the system. Equipped with jet pumps and injection nozzles, it injects water into the sediment bed to fluidize the material under low-pressure, enabling re-suspended sediment transport by ambient currents or gravity (Kirichek *et al.*, 2021b). This approach preserves sediment within the aquatic environment while restoring navigational conditions. WIDs are particularly effective in fine-grained, cohesive sediments and confined port areas such as quay walls, turning basins, and corners where conventional dredgers are less efficient. In sandy environments, they can also be applied to fluidized sediment and transport it for short distances, where the objective is to level bed irregularities by flattening peaks and troughs rather than relocating sediment.

In some cases, WID workability is constrained by tidal conditions, as favorable operation typically coincides with ebb tide when sediment transport is strongly influenced by tidal currents. Water injection dredging uses controlled water injection to loosen and fluidize bed material, which is subsequently transported by natural hydrodynamic processes (Figure 1.4a). Unlike traditional linear dredging of reallocating offshore, this technique keeps sediment within the water system and offers a relatively low-emission solution (Kirichek and Rutgers, 2020; Prins, 2024).

Re-circulation dredging is another maintenance strategy in which sediment is suctioned from the bed and immediately released back into the water column, forming a more fluid and navigable mud layer without removing material from the port (Figure 1.4b). This process temporarily reduces the mud's yield stress and alters its settling behavior, while changes in bulk density remain limited. Re-circulation dredging focuses on re-conditioning rather than removing sediment, improving navigability while retaining material within the system (Chamanmotlagh *et al.*, 2024).

Understanding these processes is essential when evaluating how sediment re-suspension strategies interact with navigational safety, environmental thresholds, and operational constraints. This underscores the importance of integrating hydrodynamic forecasts, vessel scheduling, and sediment behavior into decision-making to ensure that each strategy is applied under conditions that maximize sediment mobility while maintaining safe navigation (Neumann *et al.*, 2024).

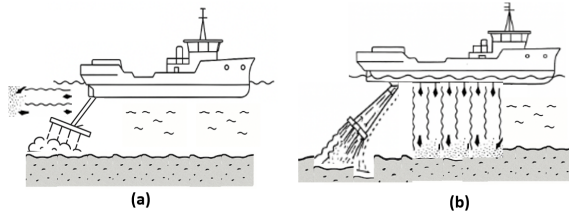


Figure 1.4.: Maintenance dredging with sediment re-mobilization using (a) Water Injection Dredging, and (b) Re-circulation Dredging.

MITIGATION MEASURES

A range of mitigation measures has been developed to reduce sediment intrusion without relying solely on traditional dredging. These methods aim to prevent sediment accumulation, promote natural dispersion, or concentrate sediment in designated areas for easier removal. The selection of appropriate techniques depends on sediment characteristics, hydrodynamic conditions, and project-specific constraints.

Sediment traps involve over-depth excavation of localized seabed areas to capture and retain incoming sediment (See Figure 1.5a). These traps simplify dredging operations by concentrating sediment in predefined zones, allowing for more efficient removal (Saichenthur *et al.*, 2020). Air bubble screens create vertical curtains of rising bubbles that act as dynamic barriers (See Figure 1.5b). These screens redirect sediment-laden flows and reduce deposition by leveraging buoyancy and turbulence to keep particles suspended (Vahaji *et al.*, 2019). Current deflecting walls are structural barriers designed to alter local hydrodynamics (See Figure 1.5c). By redirecting water flow, these walls prevent sediment deposition in sensitive zones and guide suspended particles toward offshore areas where accumulation is less problematic (Wang *et al.*, 2022).

Sediment wash-out systems are non-extractive sediment management techniques designed to prevent accumulation rather than remove it. They work by injecting high-pressure water jets into the seabed or sediment layers to fluidize deposited sediment (See Figure 1.5d). This process keeps the sediment in suspension, allowing natural water currents to disperse it away from critical zones like navigation channels or port basins (Bianchini *et al.*, 2020; Pellegrini *et al.*, 2020).

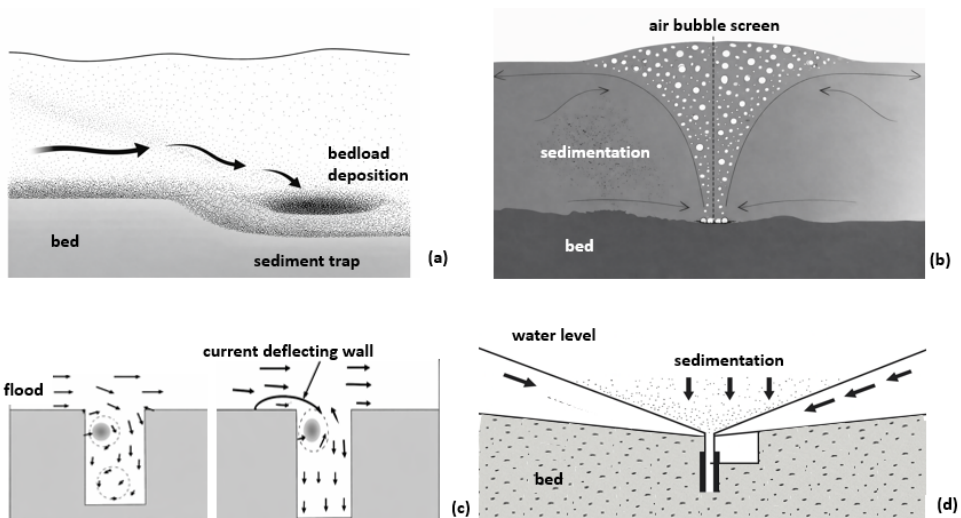


Figure 1.5.: Application of mitigation measures in port maintenance using (a) sediment trap, (b) air bubble screen, (c) current deflecting wall (modified from Winterwerp, 2023), and (d) sediment wash-out system (modified from Barth *et al.*, 2016).

The effectiveness of mitigation measures depends on site-specific factors such as sediment type, flow regime, and equipment availability. Sediment reallocation, sediment re-mobilization, and applying mitigation measures are not mutually exclusive in the port maintenance context, but each of these methods can be a part of a wider port maintenance strategy.

1.1.3. STAKEHOLDER PERSPECTIVES

Historically, cost and time have always been the main aspects to be controlled in port maintenance projects. During the last two decades, there has been societal pressure on both port authorities and contractors to pay more attention to other aspects of port maintenance, such as smartness, sustainability, and circularity, but the lack of a clear framework inhibits stakeholders' progress toward smart, sustainable, and circular port maintenance (Sugrue and Adriaens, 2022).

Smartness can be implied as using digital technologies to increase the efficiency of port maintenance, e.g., by using intelligent navigation systems and devices that adjust the dredging job most efficiently by changing vessel settings (Mikac *et al.*, 2022; Wang *et al.*, 2022). **Sustainability** can be addressed by mitigating greenhouse gas emissions, controlling the water turbidity caused by dredging works, minimizing carbon footprint, and avoiding the generation of underwater sound to protect the flora and fauna (Laboyrie *et al.*, 2018; Han *et al.*, 2022; Donázar-Aramendía *et al.*, 2024). **Circularity** can be seen by managing the dredged sediments, developing harmless methods for re-allocating contaminated sediments, and beneficially reusing dredged material (Mills and Kemps, 2016; Crocetti *et al.*, 2022; Nguyen *et al.*, 2023b). Increasing attention to these challenges in port maintenance forces port authorities and contractors to make trade-offs when quantifying environmental, operational, and economic criteria. Finding trade-offs for cost and time can be easily quantified from the viewpoint of both port authorities and contractors, while there is uncertainty when addressing the aspects of smartness, sustainability, and circularity. The vagueness of the context and application of these concepts, and the different driving factors of each stakeholder, make it difficult for port authorities and contractors to contribute.

Stakeholder demands play a central role in shaping maintenance dredging strategies, yet they are often articulated without full awareness of their operational implications. Port authorities may impose requirements such as maximum emission thresholds or strict accessibility targets, while dredging companies frequently propose innovative methods or equipment upgrades. However, these demands and offers are rarely accompanied by transparent evidence of how they translate into project-level effects. This lack of clarity can hinder rational negotiation and slow the adoption of more sustainable or circular strategies. A key motivation for this thesis is therefore to develop methods that make such demands and innovations comparable, measurable, and decision-ready, enabling stakeholders to engage in discussions grounded in operational realities rather than abstract ambitions.

1.1.4. REAL-WORLD CASES

Several major European ports have progressively integrated elements of smartness, sustainability, and circularity into their maintenance dredging strategies. These initiatives reflect a broader transition from reactive, volume-oriented dredging toward data-informed, environmentally constrained, and resource-aware sediment management. The following cases illustrate how these concepts are operationalized in practice, while also highlighting persistent research gaps identified in the scientific literature.

PORT OF ROTTERDAM, NETHERLANDS

The Port of Rotterdam (PoR) has established itself as a front-runner in smart sediment management through the PRISMA (PRogramme Innovative Sediment MANagement) framework, which combines monitoring, modeling, and decision-support tools to improve maintenance dredging efficiency (Kirichek *et al.*, 2021a). Research into water injection dredging and potential mitigation measures for reducing sediment intrusion in port basins aims to make maintenance dredging more efficient, lower CO₂ emissions, and reduce disruption to port operations. The port has a clear focus on implementing new maintenance strategies to promote circularity and climate-neutral execution of dredging operations (Hupkes *et al.*, 2025). Demonstration projects include the use of hydrogen fuel-cell-powered auxiliary equipment, such as the crane tested on the Medusa 2 dredger, illustrating the technical feasibility of near-zero-emission components in dredging operations (Notteboom and Haralambides, 2023; S. Xu *et al.*, 2025). From a circularity perspective, initiatives such as the SURICATES project aim to promote the beneficial reuse of dredged sediment by aligning reuse opportunities across regional infrastructure, ecological, and spatial planning stakeholders (Wijdeveld *et al.*, 2024).

Despite these advances, the scientific literature emphasizes that the combined effects of predictive modeling, low-emission technologies, and sediment reuse strategies are rarely assessed in an integrated manner. Most studies and pilot projects evaluate individual measures in isolation, without systematically quantifying their cumulative impacts on dredging intensity, emissions, long-term maintenance costs, or circular resource flows. This lack of system-level evaluation limits the ability to assess whether smart, sustainable, and circular interventions reinforce or constrain one another over extended time horizons (Bridges *et al.*, 2018; Sepehri *et al.*, 2024a).

PORT OF HAMBURG, GERMANY

The Port of Hamburg faces persistent challenges related to fine and contaminated sediments transported downstream by the Elbe River. Because offshore reallocation of these materials is restricted, Hamburg has developed an integrated land-based sediment treatment and reallocation strategy. A central element of this approach is the METHA (MEchanical Treatment and Dewatering of HARbour-sediments) facility, which separates reusable sand fractions from contaminated silt (Detzner *et al.*, 1998). Clean sand is reused in construction applications, while de-watered fine sediments are stored in engineered mounds or applied as sealing material (Detzner *et al.*, 2004). The port authority also applies smart port technologies, including sensor networks, vessel traffic management systems, and digital scheduling tools, to coordinate dredging operations with intensive port traffic. These data-driven measures reduce idle times and operational conflicts, indirectly contributing to emission reductions. From a sustainability perspective, the port's sediment management concept emphasizes limiting annual dredging volumes through engineered river and channel interventions, thereby reducing repeated disturbance and energy consumption. Operationally, tools such as bed levelers are used to maintain shallow areas efficiently, avoiding deployment of more energy-intensive dredging equipment where fine adjustments suffice (Kapkaeva *et al.*, 2021).

While Hamburg's sediment strategy is technically mature, the literature identifies several unresolved issues. First, the long-term environmental performance, life-cycle emissions, and economic costs of the METHA treatment–reuse–storage chain have not been comprehensively compared with alternative sediment management strategies. Second, although smart port tools are well developed, their quantitative influence on system-level dredging demand and emissions remains insufficiently analyzed. Finally, the cumulative effectiveness of engineered river interventions in reducing maintenance dredging has not been fully evaluated in relation to the natural sediment dynamics of the Elbe estuary, leaving uncertainty about long-term robustness under changing hydrological conditions (Knüppel, 2012; Carreira *et al.*, 2025).

PORT OF ANTWERP–BRUGES, BELGIUM

The Port of Antwerp–Bruges experiences continuous sedimentation across its extensive dock system and access channels, necessitating frequent maintenance dredging. To manage this complexity, the port integrates real-time water-quality monitoring, dock-water management systems, and sensor-based environmental observations that support anticipatory decision-making under ecological and operational constraints (Van de Keybus *et al.*, 2010; B. Van Maren and Van Kessel, 2016). A cornerstone of Antwerp's sediment management strategy is the AMORAS installation, which mechanically dewateres and treats several hundred thousand tonnes of dredged sediment annually, ensuring safe handling of historically contaminated materials while recovering reusable fractions. In recent years, Antwerp–Bruges has increasingly adopted circular principles by reusing suitable dredged sediments in port development projects, including terminal expansions, landscaping, and land-formation works. This practice reduces demand for imported fill materials and lowers associated CO₂ emissions from transport and primary material production (Van Esbroeck *et al.*, 2013).

Nevertheless, the literature highlights persistent gaps. The relative performance of mechanical dewatering systems such as AMORAS versus alternative strategies, including hydrodynamic or nature-based sediment management approaches, has not been systematically compared in terms of cost, emissions, and environmental impact. Moreover, although sediment reuse is expanding, criteria for matching sediment characteristics to specific reuse applications remain fragmented and project-specific, hindering quantitative assessment of circularity at the port-system scale (Coulet *et al.*, 2016; Bridges *et al.*, 2018; Carreira *et al.*, 2025).

PORT OF DELFZIJL, NETHERLANDS

The Port of Delfzijl, operated by Groningen Seaports, operates under ecologically stressed conditions in the Ems estuary. The maintenance strategy of the port is currently focused on retaining dredged sediment within the port system instead of reallocating it offshore. Fine, saline sediment is pumped into controlled drying fields, where natural desalinization and consolidation processes gradually transform it into mature

clay suitable for coastal defense applications. The ripened clay has been used to reinforce dikes, converting maintenance sediment into a coastal safety resource (Sittoni *et al.*, 2019). From a sustainability perspective, Groningen Seaports has also incorporated environmental performance into procurement decisions. For example, maintenance dredging has been executed using the LNG-powered TSHD Ecodelta, reducing emissions compared with conventional diesel-powered vessels.

Despite the promise of clay ripening, the scientific literature notes that such circular strategies have rarely been evaluated through systematic comparison with conventional linear sediment reallocation options. As a result, their relative performance in terms of cost efficiency, greenhouse gas emissions, long-term sediment balance, and ecosystem recovery remains only partially understood. This lack of comparative assessment limits the transferability of clay ripening from pilot-scale implementation to broader sediment management portfolios (Koster *et al.*, 2023).

PORT OF RAMSGATE, UNITED KINGDOM

The Port of Ramsgate illustrates how small and medium-sized ports adapt maintenance dredging strategies under financial, environmental, and operational constraints. The port has transitioned from traditional mechanical grab dredging toward hydraulic dredging using WIDs. This shift reflects the need to reduce fuel consumption, operational costs, and environmental impacts, particularly given the port's proximity to protected chalk reefs and sensitive marine habitats. By mobilizing sediment during favorable tidal conditions, Ramsgate relies on natural hydrodynamic processes rather than intensive mechanical excavation, reducing the carbon footprint per dredging cycle (Prins, 2024).

While this approach demonstrates an effective balance between navigability, cost control, and environmental compliance, its long-term performance remains insufficiently documented. Existing evaluations are typically conducted on a cycle-by-cycle basis, and the cumulative effects of repeated hydrodynamic dredging on sediment transport and depth reliability have not been systematically assessed. This gap highlights the need for developing sustainable sediment management strategies based on system-scale studies to compare hydraulic and mechanical dredging operations under varying hydrodynamic conditions (Pledger *et al.*, 2020).

1.2. PROBLEM STATEMENT

The real-world cases demonstrated that, although ports are experimenting with smarter, cleaner, and more circular maintenance approaches, these efforts lack a unified quantitative framework to guide decision-making. Smart, sustainable, and circular strategies are receiving increasing attention in port maintenance, yet these value dimensions remain insufficiently quantified for use in real-world decision-making. Because they lack clear definitions, quantification methods, and operational indicators, they are rarely integrated into the selection of maintenance dredging strategies. As a result, strategy selection continues to be dominated by cost and time, despite growing environmental and societal expectations.

1.3. RESEARCH GAP

Current literature discusses sustainability, circularity, and smart operations largely at a conceptual level, but it does not provide practical methods that translate these concepts into quantifiable, comparable, and operational indicators that can support decision-making at the project level. Moreover, existing tools used by industry, such as production estimations, cost calculations, and discrete-event planning models, focus predominantly on time and cost, offering no mechanism to incorporate broader value dimensions. This gap limits the ability of port authorities and dredging contractors to include smart, sustainable, and circular considerations in evidence-based selection of maintenance dredging strategies.

1.4. RESEARCH OBJECTIVE

The objective of this research is to develop a method that makes smart, sustainable, and circular value dimensions quantifiable, through quantifiable indicators and trade-off analyses, to enable their systematic inclusion in the selection of port maintenance strategies.

1.5. RESEARCH QUESTIONS

The research objective leads to the following main question: **How can smart, sustainable, and circular strategies be made quantifiable to support trade-off analyses and informed selection of port maintenance strategies?** To answer this, each value dimension will be clarified, quantified, and linked to case studies where its operational implications can be evaluated. The following sub-questions structure this investigation:

- **Sub-question 1.** *How are smartness, sustainability, and circularity defined in the literature and interpreted by port authorities and contractors?*
- **Sub-question 2.** *How can smart, data-driven methods quantify the interaction between seagoing processes and maintenance dredging?*
- **Sub-question 3.** *How can the sustainability impacts of maintenance dredging equipment selection be quantified?*
- **Sub-question 4.** *How can the circularity aspect of sediment-reuse strategies be quantified and distinguished from traditional linear maintenance methods?*

Together, these sub-questions provide a comprehensive basis for incorporating smartness, sustainability, and circularity into strategy selection beyond traditional time–cost considerations.

1.6. RESEARCH OUTLINES

This dissertation is structured as follows. Chapter 2 presents a literature study focusing on defining implications of smartness, sustainability, and circularity in port maintenance from the perspective of dredging contractors and port authorities as the main stakeholders. This review results in a clearer definition of each aspect when each stakeholder considers its own requirements, when analyzing the previous research. Chapter 3 analyzes the interference between seagoing and maintenance dredging processes using data-driven methods. This enables the application of smart, data-driven approaches that substantially reduce seagoing vessel delays during port calls and significantly mitigate operational disruptions. Chapter 4 concentrates on quantifying a trade-off between time and emission for different maintenance dredging strategies. The chapter introduces a transparent method for estimating cost, emissions, production rate, and project duration, and critically examines each Key Performance Indicator (KPI) to clarify how these metrics can support more informed strategy selection in future maintenance projects. Chapter 5 explores the potential reuse of dredged sediment for dike reinforcement and contrasts it with conventional offshore reallocation. Key KPIs are quantified for both scenarios to enable a direct comparison. Chapter 6 elaborates on what are the main research limitations and how this dissertation contributes to the existing literature. Chapter 7 concludes the findings of this dissertation, answers the research questions, and provides recommendations for further research.

2

LITERATURE REVIEW

A problem well stated is a problem half solved.

Charles F. Kettering

This chapter addresses "Sub-question 1: How are smartness, sustainability, and circularity defined in the literature and interpreted by port authorities and contractors?" by systematically examining how smartness, sustainability, and circularity are defined and operationalized in the literature on port maintenance dredging. The chapter applies a Systematic Literature Review (SLR) combined with the Frame of Reference (FoR) method to structure and compare perspectives from port authorities and dredging contractors. A total of 128 peer-reviewed journal articles, conference papers, and authoritative industry publications are analyzed and mapped onto the FoR elements: strategic objectives, operational objectives, quantitative state concepts, benchmarks, intervention procedures, and evaluation procedures.

The results show that the literature exhibits substantial convergence at the strategic level, where goals such as safeguarding accessibility, reducing environmental impact, and improving sediment management efficiency are widely shared. However, pronounced divergence emerges at the operational level. Indicators, benchmarks, and decision recipes are often inconsistently defined or remain implicit, particularly for smart port applications and emission mitigation. Circularity-related studies frequently lack clearly defined spatial and temporal system boundaries, limiting their applicability to operational decision-making.

The chapter concludes that existing research provides a rich conceptual foundation but insufficient methodological support for trade-off analysis at the project level. By explicitly identifying where FoR elements remain undefined or misaligned across stakeholders, this chapter establishes the conceptual gaps that motivate the development of the quantitative, event-based methods applied in Chapters 3, 4, and 5.

This chapter is based on a published review paper:

A. Sepehri, A. Kirichek, M. Van den Heuvel, and M. Van Koningsveld (2024a). "Smart, sustainable, and circular port maintenance: A comprehensive framework and multi-stakeholder approach". In: *Journal of Environmental Management* 370, p. 122625. ISSN: 0301-4797. DOI: 10.1016/j.jenvman.2024.122625

2.1. INTRODUCTION

The growing demand for transportation in support of global waterborne trade has triggered competition among ports worldwide to attract new maritime traffic and shipping routes. The quality of port and waterway infrastructure affects the average waiting time of vessels and directly influences the tendency of shipping companies to favor a specific port or route within a region (UNCTAD, 2023). Consequently, port and waterway authorities are continuously engaged in extensive infrastructure investments and the exploration of maintenance strategies aimed at optimizing the efficiency and functionality of their operations.

Van Koningsveld *et al.* (2023) argued that ports and waterways should be viewed as parts of a coherent system that supports waterborne supply chains and that their integral design and operation are essential. Variations in waves, currents, and sediment transport cause sedimentation in ports and waterways. These sedimentation processes bear substantial consequences for port accessibility, resulting in partial or complete obstruction of port operations (Bakker *et al.*, 2024). The inaccessibility of a port means that vessels cannot (readily) access berth areas, and delays in cargo handling cause significant economic losses. Consequently, such ports lose reliability in the eyes of shipping companies, which may opt for alternative, more reliable ports. To solve this problem, maintenance dredging and mitigation measures come into play to remove, mobilize, or bypass sediments, ensuring continued accessibility in ports and waterways (Wan *et al.*, 2018).

Historically, cost and time have always been the main aspects to be controlled in port maintenance projects. During the last two decades, there has been societal pressure on both port authorities and contractors to pay more attention to other aspects of port maintenance, such as smartness, sustainability, and circularity, but the lack of a clear framework inhibits their progress toward these concepts. Smartness can be implied as using digital technologies to increase the efficiency of the port maintenance, e.g., by using intelligent navigation systems and devices that adjust the dredging job most efficiently by changing vessel settings (Mikac *et al.*, 2022; Wang *et al.*, 2022). Sustainability can be addressed by mitigating greenhouse gas emissions, controlling the water turbidity caused by dredging works, minimizing carbon footprint, and avoiding the generation of underwater sound to protect the flora and fauna (Laboyrie *et al.*, 2018; Han *et al.*, 2022; Donázar-Aramendía *et al.*, 2024). Circularity can be seen by managing the dredged sediments, developing harmless methods for disposing of contaminated sediments, and beneficially reusing dredged material (Mills and Kemps, 2016; Crocetti *et al.*, 2022; Nguyen *et al.*, 2023b).

Increasing attention to these challenges in port maintenance leads port authorities and contractors to compromise on the quantification of these criteria. Finding trade-offs for cost and time can be easily quantified from the viewpoint of both port authorities and contractors, while there is vagueness when addressing smartness, sustainability, and circularity aspects. The vagueness of the context and application of these concepts, and the different driving factors of each stakeholder, make it difficult for port authorities and contractors to contribute. To improve this issue, this study investigates the mentioned gap by applying the FoR method (Van Koningsveld and Mulder, 2004) to define objectives and indicators for decision-making from both the port authorities and the contractors' perspectives.

The increasing emphasis on incorporating smart, sustainable, and circular practices into port maintenance introduces complex challenges that go beyond traditional cost and time considerations. The absence of a clear framework for integrating these elements complicates the decision-making process, making it difficult for port authorities and contractors to achieve balanced and effective solutions. This study applies the FoR approach to systematically define objectives, performance indicators, and evaluation criteria. An essential element of the FoR approach is a basic template that conveniently outlines the minimum number of elements that need to be made explicit when dealing with a decision problem. Elements that remain empty or undefined can be regarded as challenges for the decision problem at hand. To determine which challenges exist in the context of smart, circular, and sustainable port maintenance, an extensive literature review is required. Therefore, The FoR approach is coupled with a SLR method to investigate the most relevant research papers published in this field, classify the main challenges, and identify the knowledge gaps. These two approaches not only highlight how the problem is viewed from both port authorities' and contractors' perspectives but also expose the driving factors in implementing each of these criteria in port maintenance. Furthermore, remaining challenges can be revealed, and subjects that require further investigation can be identified.

The subsequent sections of this paper are organized as follows. Section 2.2 describes the FoR and SLR approaches employed in this study. Section 2.3 discusses the articles extracted during the review and analyzes them thoroughly using the elements of the FoR approach for the three themes of smartness, circularity, and sustainability. Section 2.4 addresses the theoretical and managerial implications of the SLR findings and highlights knowledge gaps and future research directions. Section 2.5 summarizes the key insights and outcomes, providing a concise overview of the entire study.

2.2. METHOD

2.2.1. FRAME OF REFERENCE

The FoR approach, developed by Van Koningsveld and Mulder (2004), analyzed the particularly successful policy of dynamic coastline preservation to extract the key components that are summarized as the basic FoR template. This template has proven useful for the structured analysis of existing approaches/policies and the development of new ones. The FoR approach has been successfully applied in multiple projects to gather insights from stakeholders with different backgrounds to improve their decision-making processes. Some examples of real-world projects where the FoR approach has been successfully applied are the coastal sediment management policy in the Netherlands (Van Koningsveld and Mulder, 2004; Mulder *et al.*, 2011), the design of the navigation channel (Miedema *et al.*, 2007), the planning of beach recreation (Jiménez *et al.*, 2011), and the environmental monitoring of offshore renewable energy projects (Garel *et al.*, 2014) and the evaluation of the dredging project (Laboyrie *et al.*, 2018).

The FoR approach serves as a useful tool in quantifying trade-offs between multiple, often conflicting objectives in port maintenance, such as cost efficiency, environmental sustainability, and contribution to the circular economy. The application of FoR in real-world projects is achieved through defining clear objectives, selecting and quantifying indicators and metrics, and facilitating stakeholder communication. The basic template can be used both descriptively, to assess how well-specified existing policies are, and prescriptively, to guide the development of new policies. Every decision problem requires the specification of:

- **A strategic objective:** The strategic objective represents the long-term vision of the desired state of the system under certain consideration. It serves as the overarching goal that the policies and strategies aim to achieve.
- **An operational objective:** Operational objectives are specific, measurable objectives designed to execute the broader strategic goals in day-to-day operations. These objectives offer actionable steps to integrate solutions that exist for each relevant challenge.
- **A quantitative state concept:** For each operational objective, one or more quantifiable parameters are specified through the quantitative state concept. These parameters provide the quantitative building blocks for decision-making. They are crucial for determining indicators, benchmarking, instating the intervention procedure, and assessing whether the objectives are met.
- **A benchmarking procedure:** The benchmarking process involves comparing the quantifiable parameters to established benchmarks or reference points. This step helps assess how well the system is performing in terms of its objectives. The benchmarks are used to set performance standards and guide decision-making.
- **An intervention procedure:** Once the benchmarks are established, intervention procedures are put in place to address any gaps between the current state and the desired state. These interventions can be strategic actions, policy changes, or specific measures aimed at achieving the objectives. In any case, an intervention should be capable of achieving the desired state.
- **An evaluation procedure:** The evaluation procedure involves assessing whether the objectives have been met after implementing interventions. This step serves as a feedback loop to determine the effectiveness of the strategies and policies. It helps decision-makers to refine and adapt their approaches as needed.

Figure 2.1 shows how the above elements together form the basic FoR template and how these elements are interconnected (Van Koningsveld *et al.*, 2023).

Port authorities and contractors (e.g. dredging companies) can have different perceptions of the concepts of smartness, circularity, and sustainability in port maintenance. The FoR approach helps to make these differences explicit. The SLR is employed to extract the main perspectives from the literature and fill the basic FoR template as much as possible. The approach will reveal to what extent each of these concepts is addressed and what elements of the basic FoR template remain unspecified, or where authorities and contractors have diverging perspectives.



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consist of two parts connected by an “AND” operator: the first part is a combination of synonyms for each subject, and the second part is a combination of relevant terms for port maintenance. Keywords are formulated so that they are most likely to return all relevant search results. For example, using “smart” as a keyword includes search results for “smarter” or “smartness” and the same applies to using “circular”, which includes search results for “circularity”. The keywords and queries listed in Table 2.1 are used for the search in the Scopus database.

Table 2.1.: Selection of keywords and queries for SLR.

Port maintenance aspect	Query
Smartness	(smart OR intelligent OR simulation OR ai OR (artificial AND intelligence) OR (machine AND learning)) AND (port AND ((maintenance AND dredging) OR (sediment AND reallocation) OR (sediment AND remobilization) OR (sediment AND bypass) OR (prevent AND sediment)))
Sustainability	(sustainable OR sustainability OR environment OR turbid OR emission OR (water AND quality) OR noise) AND (port AND ((maintenance AND dredging) OR (sediment AND reallocation) OR (sediment AND immobilization) OR (sediment AND bypass) OR (prevent AND sediment)))
Circularity	(circular OR (beneficial AND reuse) OR (nature-based AND solutions)) AND (port AND ((maintenance AND dredging) OR (sediment AND reallocation) OR (sediment AND remobilization) OR (sediment AND bypass) OR (prevent AND sediment)))

The search results showed that Scopus returned more relevant articles on the subjects of interest. Based on the results of the query, an initial pool of publications is created before they are filtered and analyzed. Inclusion and exclusion criteria are defined in Table 2.2 to find out which articles align with each subject and how the recent trend of research in each subject can be determined. The main aim is to limit the articles to English and accessible articles published since 2000. Review articles, conference reviews, and lecture notes are excluded from the search results to ensure that unique research papers are studied in the SLR. The search is focused on the research articles and conference proceedings that have contributed to the subject. Besides, a large piece of knowledge has been provided by industrial publishers (e.g. International Association of Dredging Companies (IADC), World Organization of Dredging Associations (WODA), Central Dredging Association (CEDA), and World Dredging Congress (WODCON)) that are included in the search separately.

Table 2.2.: Exclusion (EXC) and inclusion (INC) criteria for data filtering.

Criterion	Description
EXC1	Excluding the studies published before 2000
EXC2	Excluding the studies that are not accessible
EXC3	Excluding the studies that are not written in English
EXC4	Excluding the review articles, conference reviews, and lecture notes
EXC5	Excluding the studies that do not fit the context of smart, circular, and sustainable port maintenance
INC1	Including university theses and studies published by IADC, WODA, CEDA, and WODCON

The criteria listed in Table 2.2 are used to filter the search results and determine the final number of publications reviewed in each category. The results of SLR and the categorization of the problem based on the FoR approach are discussed in the next section.

2.3. RESULTS

Section 2.3.1 provides a descriptive analysis of the literature retrieved after applying the queries and filtering steps. Once the final pool of studies to be reviewed has been found, the selected period is divided into two similar periods (2000–2011 and 2012–2024), and a statistical analysis is performed for each period. This approach helps to visualize the ongoing trend in the different subjects and to find out what subjects have been studied in recent years compared to the years before. Sections 2.3.2, 2.3.3, and 2.3.4 describe the results of projecting these SLR findings onto the FoR template for the subjects of smart, sustainable, and circular port maintenance strategies, respectively. Each subject is considered from both the port authority’s and the contractor’s perspective. Separate tables are provided for each classification to identify any differences in perception and the significance of any knowledge gaps.

2.3.1. DESCRIPTIVE ANALYSIS

This section provides a descriptive analysis of the literature retrieved after applying the queries and filtering steps. Once the final pool of studies to be reviewed has been found, the selected period is divided into two similar periods (2000–2011 and 2012–2024). A statistical analysis is performed for each period. This approach helps visualize the ongoing trend in the different subjects and determine which subjects have been studied more recently compared to previous years. The following sections describe the results of projecting these SLR findings onto the FoR templates for the subjects of smart, sustainable, and circular port maintenance strategies, respectively. Each subject is considered from both the port authority's and the contractor's perspective. Separate tables are provided for each classification to identify any differences in perception and the significance of any knowledge gaps.

The search results include the publications found in the categories of smartness, sustainability, and circularity for port maintenance strategies. Figure 2.2 shows the data collection process and the number of articles (N) removed at each step when using the inclusion and exclusion criteria presented in Table 2.2.

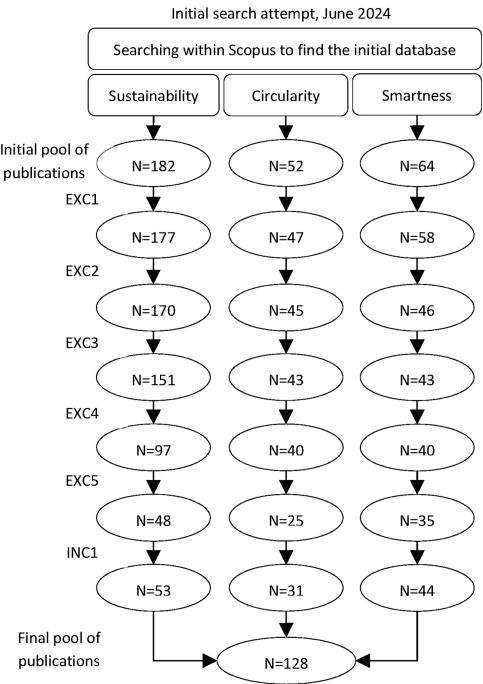


Figure 2.2.: Data collection process.

This data collection and screening process resulted in a final pool of articles aligned with the research's focus on strategies related to smartness, circularity, and sustainability in port maintenance. To make sure that the final selection of studies is consistent and content-wise relevant, the first pool of publications was extensively refined to ensure all included articles fit the context. With the retrieved data from the SLR steps, 298 articles were obtained in the initial pool, and a total of 128 articles were studied in the SLR after implementing inclusion and exclusion criteria.

The affiliation of the authors of the reviewed studies shows that the Netherlands is the leading country in the number of publications on smart, circular, and sustainable port maintenance. It is followed by the United States, China, Italy, and Spain, showing a strong record of innovation in the field of maritime technology and a significant interest in addressing the challenges of sustainable port operations in these countries (see Figure 2.3).

A total of 128 articles published between 2001 and 2024 shows that the number of publications has been steadily increasing over the past two decades, with a notable surge in the past five years (see Figure 2.4).



Figure 2.3.: Country-wise analysis of the reviewed studies.

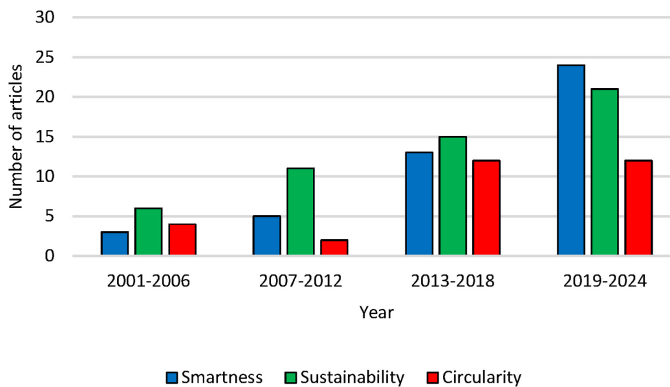


Figure 2.4.: Year-wise analysis of the reviewed studies.

This growing interest is driven by the increasing demand for sustainable and environmentally friendly practices in port operations. Figure 2.5 shows the most studied challenges, including:

- Water-related sustainability challenges (turbidity, underwater noise, contaminated sediments);
- Air-related sustainability challenges (greenhouse gas emissions, energy consumption, alternative fuels);
- Managing dredged sediments in an environmentally responsible manner;
- Enhancing the efficiency of port processes through smart technologies; and
- Implementing predictive maintenance strategies.

The frequency of articles addressing these challenges has evolved, with a significant increase in research on smartness and sediment management in recent years. This shift reflects the growing recognition of these topics as critical components of sustainable port maintenance.

Figure 2.6 shows academic journals and industrial publishers that have published articles on port maintenance that specifically address the criteria of smartness, circularity, and sustainability. The distribution of different publishers separates the number of publications into two periods. During the first period (2000-2012), industrial publishers made the main contribution to this field of research, while a notable transition to academic journals was shown during the second period (2013-2024). In this regard, journals such as “The Journal of Environmental Management”, “Ocean Engineering”, “Journal of Soils and Sediments”, and “Transportation Research Part E” have published a considerable number of articles, while “Marine Pollution Bulletin” remains an important journal in both intervals due to its focus on marine environmental challenges.

An analysis of keywords shown in Figure 2.7 revealed a clear trend towards more focused research on port processes and smartness strategies in recent years. This emphasis is evident in the increasing use of keywords



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Key findings from the SLR show an increase in attention to the scope of this study. Older articles concentrated on the viewpoint of a single stakeholder, while recently published articles provide a more holistic view into the subjects of smartness, sustainability, and circularity. This transition is observed in the aim and scope of the journals that contributed to this subject recently, and the main keywords used in the mentioned studies. In the next section, the FoR approach is applied to gain a deeper understanding of the challenges identified in this section. Furthermore, the FoR framework provides a systematic way to identify relevant indicators and develop intervention procedures for addressing these challenges for developing new smart, sustainable, and circular port maintenance solutions.

2.3.2. SMART PORT MAINTENANCE

As global trade and shipping activities evolve, port maintenance becomes a critical factor in keeping the harbors and channels navigable and fostering sustainable practices. The integration of advanced technologies and methodologies into maintenance dredging processes offers various benefits, including an increase in process efficiency, crew up-skilling, and the implementation of predictive measures. The implementation of these technologies should align with the viewpoints of both contractors and port authorities.

CONTRACTOR'S PERSPECTIVE

Contractors view smart port maintenance as a strategic approach to optimizing the efficiency and effectiveness of dredging operations while minimizing costs and environmental impact. Employing smart port maintenance techniques helps contractors improve the planning of the equipment by adopting advanced technologies.

Modern Trailing Suction Hopper Dredger (TSHD)s equipped with automation systems can be controlled with integrated computer systems from the bridge. Braaksma *et al.* (2007) discussed a control system that helps the operators on the vessel's bridge to optimize the efficiency of the dredging process. Multiple scenarios considering different sediment properties are simulated to compare the dredged volumes per dredging cycle. Estimating the performance of excavation, sedimentation, pipeline transport, and discharge processes in a TSHD was discussed by Stano (2013) and Stano *et al.* (2014), who employed a non-linear Bayesian algorithm to estimate the production parameters. Thereafter, they conducted multiple numerical simulations of the loading operation to achieve the highest efficiency for different setups. Similarly, Yue *et al.* (2015) adopted a quantitative classification model coupled with rough-set theory and conditional entropy to estimate the production efficiency of a TSHD considering the impact of sediment and underwater conditions. Estimating the production of a TSHD was further elaborated by Van Rhee (2002), Wangli *et al.* (2007), Su *et al.* (2017), Li *et al.* (2017), Sloof (2017), R. Tang and Fu (2020), Mao *et al.* (2022), and Y. Hao *et al.* (2022) to achieve the optimal control strategy in the loading phase of a TSHD when real-time evaluation of the dredging performance is included. A production model for the draghead was then formulated by De Jonge (2017), who simulated different dredging scenarios by changing the physical parameters of the loading phase. Predicting the suction density of the sediments in a TSHD was discussed by G. Hao *et al.* (2020), who proposed a meta-heuristic algorithm to optimize extreme learning machine models and build an output simulator for suction density. Later, the quantitative relation between the performance of a TSHD and operational parameters was discussed by H. Tang *et al.* (2021), who coupled deep learning and human knowledge. They collected the big sensor data and quantified the mentioned relation by solving a sparse optimization problem. Estimating the production of a TSHD was further elaborated by Bai *et al.* (2021) by adopting the ReliefF-Granger algorithm for data analysis and Artificial Intelligence (AI) to extract the significant factors in calculating the production.

Applying data-driven methods in the dredging process can help contractors explore new opportunities to employ multiple soil, vessel, and site conditions along with environmental regulations. R. Mourik and Osnabrugge (2015) discussed the devices and sensors in the new vessels that can be used to measure the production of vessels. Bokuniewicz and Jang (2018) analyzed how the sensors and location-tracking systems can be used to monitor the real-time location of dredging vessels. These systems provide heatmaps in which various intensities of colors represent the frequency of vessel presence in each designated area. Evaluating the project duration, the beginning of the job, and risk probability is vital for contractors before submitting a tender. Chou and Lin (2020) employed a Monte Carlo simulation coupled with a stochastic machine learning approach to assess the uncertainty of project duration in the initial phase of tendering. An agent-based simulation is another research method to connect numerous operational variables of a dredging process. De Boer *et al.* (2022) introduced an agent-based simulation package based on discrete events that define multiple objects that interact during the simulation process. This package is also applied by de Boer *et al.* (2023b) to investigate the interaction of different dredging equipment when the number of each equipment and the total amount of dredged sediment are adjustable.

Up-skilling the dredging crew using simulators is addressed by B. Mourik and Braadbaart (2003) and Van Muijen *et al.* (2003). The goal of these simulators is to achieve the highest efficiency for dredging vessels and to mitigate the breakdowns and environmental impact of the dredging processes. Virtual 3D dredging sites in simulators provide trainees with hands-on experience in dredging techniques, automation systems, data analysis, and onboard diagnostics.

The mentioned literature described numerous examples from the literature that could be classified as smart port maintenance practices from a contractor's perspective. The strategic objective that encapsulates all of these examples can be formulated as "*To execute port maintenance in the most efficient way of using the dredging equipment*".

PORT AUTHORITIES' PERSPECTIVE

Port authorities aim to maintain efficient and safe navigation of seagoing vessels to facilitate port processes and prevent disruptions. To ensure this, berth areas, turning basins, and navigation channels should remain at the required depth to reduce the risk of groundings and delays. Meanwhile, port maintenance operations might interfere with the port processes and cause delays for seagoing vessels that intend to be served in a terminal. Smart practices are helpful in better planning maintenance works, improving the efficiency of port processes, mitigating the corresponding costs, and minimizing environmental impacts.

Skibniewski and Vecino (2012) introduced a web-based project management framework to improve the performance of port maintenance projects. This framework, which is used to optimize the cycle time of processes, can be aligned with the contractors' business rules by generating several scenarios and estimating the cost efficiency of each scenario. On the other hand, analyzing spatial and temporal data helps port authorities in the predictive maintenance of ports and waterways when it is coupled with monitoring the bathymetry data (Xin *et al.*, 2022). The bathymetry data is further used by Hu *et al.* (2022) to monitor the impact of dredging on sedimentation patterns in the future and optimize the efficiency of dredging processes.

The budgeting problem for maintenance dredging projects is discussed by Mitchell *et al.* (2013), who determined an optimal budgeting scheme for multiple projects when the efficiency of port processes is also taken into account. A polynomial-time heuristic algorithm is used to optimize the problem based on maximizing the amount of cargo throughput and potential dredging scenarios. Similar research was conducted by Khodakarami *et al.* (2014), who developed a budgeting model that optimizes the benefits of multiple maintenance projects in a multi-modal transportation network. Different maintenance dredging scenarios are analyzed in terms of the required financial resources and operational efficiency. They also included the capacity of ports and the waterways network, and depth restrictions in the model. The budgeting problem was coupled with the selection of maintenance dredging strategies by Ahadi *et al.* (2018), who incorporated budget uncertainty assigned to each port district. The genetic algorithm developed in this study aims to address the disrupted flow due to the lack of sufficient depth for the navigation of seagoing vessels.

The role of machine learning and AI in port maintenance was discussed by Liu *et al.* (2019), who employed multiple machine learning algorithms to estimate the sediment types considering bathymetry and back-scatter. They proposed an efficient model that predicts the changes in sediment distribution, which can be used to preserve the water quality and control the impact on benthos. Similarly, many other articles (Goldstein *et al.*, 2019; Pham *et al.*, 2019; Mateo-Pérez *et al.*, 2021; Bashir, 2022; Houser *et al.*, 2022) investigated the application of AI in analyzing the morphological data to determine sedimentation and hydrodynamic patterns and propose novel strategies for port maintenance that have the lowest costs and minimum environmental impacts.

Analyzing the big data of pre- and post-dredging surveys conducted by Sugrue (2021) and Rahman and Ali (2022) was used to evaluate the effectiveness of maintenance dredging processes. The authors considered the largest draught of seagoing vessels when selecting the port maintenance strategies to identify the navigation issues. In this regard, predicting the sedimentation process in berths and channels is also significant when monitoring the safe navigation of vessels and planning for regular maintenance dredging. Nakagawa *et al.* (2022) utilized the obtained data from bathymetry surveys to simulate the hydrodynamics, predict the sedimentation process, and ensure efficient port maintenance. Sepehri *et al.* (2023) applied agent-based simulation to identify the interference between dredging equipment and seagoing processes in terms of the waiting time that each vessel experiences before being served in a terminal. Determining these interactions can be used to improve the port processes planning and to select port maintenance strategies by quantifying trade-offs between different indicators (e.g., cost, energy consumption, emission, etc.). Analyzing the Automatic Identification System (AIS) by Sepehri *et al.* (2024b) demonstrated the interferences of seagoing processes and maintenance dredging operations when a TSHD aimed to dredge a terminal in multiple cycles.

The waiting time of seagoing vessels due to the lack of required nautical accessibility was then quantified while monitoring the vessels' movements according to the AIS data.

The reviewed literature above elaborated on reported examples of smart practices of port maintenance from the viewpoint of port authorities. The strategic objective that encompasses all of the instances can be formulated as "*To perform cost-effective port maintenance with the least interference with port processes*".

SYNTHESIS

The FoR approach used in this chapter elaborates on how the above-mentioned strategic objectives from the contractors' and port authorities' perspectives could be further applied in practice. The obtained insights from the SLR when following the FoR template are used to develop a coherent perspective for all stakeholders. This approach helps us by (a) having more explicit perspectives on what could be considered "smart port maintenance"; and (b) showing how contractors and port authorities have different perceptions on this problem.

The results obtained from reviewing the literature show that both contractors and port authorities have different viewpoints that overlap at some points (see Table 2.3). Contractors address the efficiency of port maintenance based on the equipment's operational performance, while port authorities aim to connect it to the interaction with port processes. Outlining the downtime in both port maintenance operations and port processes can lead to a compromise between contractors and port authorities during the project implementation. Operational inefficiencies, along with port hindrances during dredging, are both associated with the cost-effectiveness of port maintenance projects. Contractors aim to improve their cost-effectiveness by achieving a holistic view of project characteristics and equipment performance, while port authorities try to have accurate estimates of the required budget. The majority of research works are done from the perspective of contractors, focusing on improving the performance of different steps of the project, with a few research papers examining how port maintenance can affect the performance of port processes.

Table 2.3.: The FoR of smart port maintenance.

Procedure	Contractor perspective	References	Port authority perspective	References
Strategic objective	Efficient port maintenance using dredging equipment	(Bai <i>et al.</i> , 2021; H. Tang <i>et al.</i> , 2021)	Cost-effective maintenance with minimal interference	(Ahadi <i>et al.</i> , 2018; Sepehri <i>et al.</i> , 2023)
Operational objective	No deviation from cycle time due to equipment or operator inefficiencies	(Bokuniewicz and Jang, 2018; Chou and Lin, 2020)	No budget overrun or deviation from predicted port cycle time	–
Quantitative state concept	Cycle-time duration, operational delays, workability downtime	(Yue <i>et al.</i> , 2015)	Estimated budget and interference duration with port processes	(Nakagawa <i>et al.</i> , 2022)
Benchmarking process	No equipment downtime due to poor performance or operator errors	–	No exceeded budget or waiting time for seagoing processes	(Hu <i>et al.</i> , 2022)
Intervention process	Rescheduling using smart, data-driven methods; operator upskilling	(De Boer <i>et al.</i> , 2022; de Boer <i>et al.</i> , 2023b)	Penalty rules for extra budget or waiting time	(Mitchell <i>et al.</i> , 2013; Khodakarami <i>et al.</i> , 2014)
Evaluation process	Real-time assessment of equipment efficiency and operator performance	(Li <i>et al.</i> , 2017; G. Hao <i>et al.</i> , 2020)	Monitoring cost-efficiency of maintenance and its interaction with port processes	(Sepehri <i>et al.</i> , 2024b)

2.3.3. SUSTAINABLE PORT MAINTENANCE

Sustainable practices in port maintenance seek to harmonize social and economic considerations to safeguard long-term ecological health while maintaining efficient maritime operations. These practices involve strategies that minimize adverse aquatic environmental impact (e.g., hydrodynamic variations, turbidity increase, and wastewater discharge), ecological impact (e.g., loss of benthos and escape of aquatic animals), and other effects (e.g., vessel exhaust emission, vessel noise emission, and dispersion of contaminated

sediments) (Han *et al.*, 2022). These effects can be controlled by minimizing dredging frequency, utilizing eco-friendly equipment, and engaging stakeholders with different perspectives.

CONTRACTORS' PERSPECTIVE

2

Contractors aim to minimize the environmental impact of port maintenance operations by adopting eco-friendly equipment that leads to fewer sediment dispersions, lower exhaust emissions, and lower noise emissions. They actively engage with local communities and stakeholders to ensure that port maintenance aligns with community values. Transparent communication, consultation with stakeholders, and collaboration with environmental organizations help contractors to achieve these goals.

Noteworthy examples from the literature review include many research papers discussing the impact of port maintenance operations on physical habitats (Gilkinson *et al.*, 2003; Hitchcock and Bell, 2004; Erftemeijer and Lewis III, 2006; Erftemeijer *et al.*, 2012), analyzing the effects of contaminated sediments on the marine environment (Guerra *et al.*, 2009), monitoring the impact of heavy metals on local habitats (Donázar-Aramendía *et al.*, 2024), and developing decision-support tools to mitigate these effects (Ramirez *et al.*, 2017). Besides, contractors follow legislation posed by their governmental and non-governmental clients. el Mahdi Safhi *et al.* (2024) analyzed the sustainability limits of managing the dredged sediments in port development projects by introducing different real-world case studies. Innovative solutions proposed by dredging companies are also discussed to draw a conclusion on which environmentally friendly approaches can be further developed for port infrastructure projects.

Dredged sediments released from dredging equipment, including TSHD overflows, disturbance in the area of dragheads and jetbars, and scouring of the seabed by propellers and bow-thrusters are the main sources of generating turbidity. By extracting real-time data on overflow losses in a TSHD, Kerssemakers (2004) and Babuska *et al.* (2006) discussed an estimation of the mixture density and flow rate. The performance of the TSHD in overflow losses was evaluated by simulating the processes with real measurements. A new computational fluid dynamics model was developed by Decrop (2015), Decrop *et al.* (2016), Decrop *et al.* (2017), and Decrop *et al.* (2018) to understand the dynamics of sediment distribution in a designated marine environment and implement mitigation measures to minimize its impact on the local habitats. Furthermore, the computational fluid dynamics modeling was applied for the sediment diffusion characteristics and their influencing factors during the overflow stage of a TSHD to minimize the pollution impact of sediment disturbance (De Wit, 2010; De Wit, 2015; Luo and Yu, 2019; Shao *et al.*, 2020). Advanced technologies on board help the crew monitor the performance of the dredging equipment in real-time and adopt control strategies where the dredging vessel has no overflow, has a certain amount of overflow, or has a controlled overflow. A trade-off analysis coupled with environmental risk assessment is proposed by Becker (2011), Dupuits (2012), Becker *et al.* (2015) to determine how the overflows affect the vessel's production and the ecological health of the surrounding environment. Bai *et al.* (2022) discussed an optimization method for the loading cycle of a TSHD in which statistical analysis and machine learning methods are employed to predict the total amount of loaded sediments in the hopper bin and the rate of overflow loss.

Underwater sound is generated by dredging equipment, jet pumps, and air bubble screens, which can be harmful to marine fauna. de Jong *et al.* (2011) discussed this challenge by providing a framework applicable to port maintenance projects to analyze the possible effect of different types of sounds generated in different places or measured by different monitoring equipment. Reine *et al.* (2014) tested this research using regular surveys that determine the relation between the generated underwater sound and the total amount of dredged sediments within a certain period.

Ytsma *et al.* (2009) discussed the relation between the amount of emissions and the fuel type in a TSHD, suggesting that dredging companies invest in the energy transition in their fleet. Shi (2013), D. de Roode (2020), and C. de Roode *et al.* (2022) discuss understanding the behavior of energy systems in a TSHD for emission reduction. Thereafter, the vessel's operational performance can be optimized while minimizing the total emissions. Automatic steering is a solution to minimize emissions discussed by Noshahri (2016) when the vessel's operation is adjusted based on the highest efficiency and environmental restrictions.

The reviewed studies discussed some instances of sustainability criteria in port maintenance from the perspective of contractors. The varied problems addressed in sustainable port maintenance result in a broad strategic objective which can be formulated as "To promote the sustainability of port maintenance operations, by preserving coastal habitats, reducing sediment dispersion, underwater sound, and greenhouse gases". Regular evaluation of the performance of sustainability practices helps contractors achieve a trade-off between equipment efficiency and environmental damage mitigation strategies (Bianchini *et al.*, 2019).

PORT AUTHORITIES' PERSPECTIVE

Port authorities aim to achieve a balance between economic development and the environmental consequences of port maintenance operations. The port authorities' initiative is to maintain the required depth of water with the least environmental impact on local habitats when collaborating with environmental agencies and local communities. These practices also incorporate monitoring water quality, total greenhouse gas emissions, and underwater sound intensity.

Bray (2008) established a holistic view of the environmental impact of dredging projects and how it affects project planning and execution. Later, Sulaiman *et al.* (2011) emphasized the port authorities' requirements for maintaining accessibility for large-draft vessels, along with comparing the sustainability aspects of different dredging strategies. Scheffler *et al.* (2014) proposed a Multi-Criteria Decision Analysis (MCDA) model to analyze the sustainability of different dredging projects. A stochastic multi-criteria acceptability analysis is proposed to determine which project contributes to each economic, social, and environmental aspect of sustainability.

Sediment dispersion is a significant issue that causes ecological risks and was addressed in different studies. Mestres *et al.* (2014) studied the impact of sediment spills from the barges used for transporting the dredged material on the surrounding marine habitats. Pellegrini *et al.* (2020) presented a technology based on a patented jet pump that maintains the water depth through continuous removal of sediments. The cost-effectiveness and environmental impact of this technology are then compared to the traditional maintenance dredging method. In another study Mikac *et al.* (2022), the efficiency of jet pumps as sediment bypassing plants is analyzed by measuring the reduction of organic matter content in the sediment and the higher diversity of fish fauna in the local environment.

The short and long-term impacts of maintenance dredging operations on the aquatic environment were discussed by Thibodeaux and Duckworth (2001) on the dispersion of contaminated sediments. Monitoring of contaminated sediment dispersion was conducted when contamination of the re-mobilized sediments by TSHDs causes serious damage to flora and fauna, especially in the displacement location of a TSHD (Ponti *et al.*, 2009; Torres *et al.*, 2009). Wasserman *et al.* (2013) proposed a new planning approach for maintenance dredging where monitoring the contaminant concentration in the sediments is a part of the environmental impact assessment. A detailed mapping of contamination is shown in divided regions, and limitations are established to avoid extra concentration of these sediments in each region. Donázar-Aramendía *et al.* (2018) and García-Oliva *et al.* (2019) employed a before-after-control-impact approach to determine the impact of port maintenance on the salt intrusion in estuaries. The authors assessed the impact of dredging on sediment and water characteristics, macro-faunal communities, and surrounding shallow water habitats. Moreover, the quality assessment of sediments was discussed by Birch *et al.* (2020) based on anthropogenic change and ecological risk in port estuaries. Miró *et al.* (2022) discussed multiple challenges, such as the impact of port maintenance on the macro-fauna of the water column in a turbid estuary. Establishing environmental limits that should be included in the port development plans is discussed by Suedel *et al.* (2024) to predict the potential adverse impacts of dredging on sensitive habitats. In this regard, the indirect effect of dredge plumes on surrounding coral habitats is assessed by developing a risk-based framework that applies preventive measures when the risk level surpasses a certain threshold.

The potential risks of underwater sound during maintenance dredging are addressed by developing a risk-based framework for different marine species (McQueen *et al.*, 2024). The framework can be used by port authorities to regulate sound emission regulations during port maintenance. Underwater sound is further analyzed by Suedel *et al.* (2019) for different phases of maintenance dredging, such as excavation, transit, and material placement. The developed risk-assessment framework in this study uses different site-specific information to evaluate the potential damage of the generated sound by each dredging phase to the flora and fauna.

Port authorities seek to minimize the impact of port maintenance operations on air quality and greenhouse gas emissions as they recognize their importance on public health and surrounding ecosystems (Horowitz, 2015). When it comes to port maintenance, one of the ambitions of port authorities is to minimize the greenhouse gas emitted from both dredging and seagoing operations, while the required water depth is maintained and port processes are not disrupted. Energy transition in dredging equipment is an emerging subject that contributes to mitigating the total emissions of the system. Ban and Bebić (2023) analyzed the opportunities for using alternative fuels in a TSHD and how the type and amount of emissions can be reduced. Nooren (2023) investigated the initiatives of Dutch port authorities in reducing carbon emissions in the maintenance dredging operations when considering the expectations of different stakeholders, such as environmental agencies.

The reviewed studies discussed how port authorities view the sustainability aspects of port maintenance.

Based on different issues elaborated in this scope, the strategic objective that encapsulates all of these issues can be formulated as “*To promote the sustainability of port maintenance operations and port processes, by imposing operating limits on habitat protection, focusing on the emissions of sediment, underwater sound, and greenhouse gas*”.

2

SYNTHESIS

The FoR approach is used to elaborate on how the mentioned strategic objectives could be further operationalized in Table 2.4. The insights obtained from the SLR coupled with the FoR template help us in (a) understanding the explicit definition of sustainable practices in port maintenance, and (b) how contractors and port authorities have different perspectives towards these practices.

The insights drawn from the literature show that, similar to the smartness aspect, contractors and port authorities address the sustainability aspects from the perspective of equipment and port processes, respectively. To ensure that sustainability criteria are followed during port maintenance projects, port authorities establish operating limits on the emissions of sediment, underwater sound, and greenhouse gases that might be harmful to local habitats. On the other hand, contractors assess their equipment performance regarding the mentioned emissions to make sure that they remain within acceptable limits and apply mitigation practices if they don't follow the regulations. The above-mentioned emissions are more frequently addressed for the dredging equipment of contractors and port authorities, mainly outlining the environmental damages of these emissions on surrounding habitats.

Table 2.4.: The FoR of sustainable port maintenance.

Procedure	Contractor perspective	References	Port authority perspective	References
Strategic objective	Promote sustainability in port maintenance by preserving habitats and reducing sediment dispersion, underwater sound, and greenhouse gas emissions.	(Bai <i>et al.</i> , 2022)	Promote sustainable port maintenance and port processes by enforcing operating limits on habitat protection and reducing sediment dispersion, underwater sound, and greenhouse gas emissions.	(Sulaiman <i>et al.</i> , 2011)
Operational objective	Sediment dispersion, underwater sound, and greenhouse gas emissions must remain within limits imposed by regulators and clients.	(Noshahri, 2016; Shao <i>et al.</i> , 2020)	Maintain port accessibility by ensuring environmental impacts remain within limits that avoid harm to local habitats.	–
Quantitative state concept	Sediment dispersion, underwater sound, and greenhouse gas emissions as a function of space and time linked to dredging equipment use.	(Ramirez <i>et al.</i> , 2017)	Acceptable environmental limits for sediment dispersion, underwater sound, and greenhouse gas emissions based on the resilience of nearby receptors.	(McQueen <i>et al.</i> , 2024)
Benchmarking process	Verify that sediment dispersion, underwater sound, and greenhouse gas emissions remain within acceptable limits; adopt mitigation if required.	–	Assess whether environmental limits ensure sustainable interaction between port and environment; adjust limits if needed.	(Scheffler <i>et al.</i> , 2014)
Intervention process	Implement reduction measures for sediment dispersion, underwater sound, and greenhouse gas emissions according to existing limits.	(Decrop <i>et al.</i> , 2018; C. de Roode <i>et al.</i> , 2022)	Set operating limits balancing economic performance of port processes with environmental impacts of maintenance operations.	(Pellegrini <i>et al.</i> , 2020)
Evaluation process	Evaluate how emission limits contribute to the sustainability of port maintenance.	(Bianchini <i>et al.</i> , 2019)	Evaluate how emission limits support sustainable maintenance while ensuring port accessibility and efficient port processes.	(Birch <i>et al.</i> , 2020; Suedel <i>et al.</i> , 2024)

2.3.4. CIRCULAR PORT MAINTENANCE

Circularity in port maintenance refers to adopting practices that minimize sediment waste and determine beneficial purposes for the collected materials. It involves dredging methods that reuse the dredged sediments in infrastructural projects instead of re-allocating them in displacement areas. During the sediment handling, extra operations on the sediments might be required, such as dewatering, treatment, and processing. Contractors and port authorities have different driving factors toward the circular practices in port maintenance, which are elaborated as follows.

CONTRACTORS' PERSPECTIVE

Contractors contribute to the circular economy by redesigning the operational cycle of equipment. It includes using pipelines to transport the sediment in designated locations or raining the sediment to the shoreline instead of re-allocating it in an offshore area. Meanwhile, the impact of these extra operations on the efficiency of the whole dredging cycle should be analyzed along with its environmental impact on the surrounding habitats (Mills and Kemps, 2016). Sediment transport for circular practices is important in determining the efficiency of reusing the dredged material and facilitating the port process. Karambas and Samaras (2014) developed a mathematical model that formulates the sediment transport in port maintenance projects to use the dredged sediments for shore protection and maximize the efficiency of dredging operations. The Kleirijperij project in the Netherlands is an instance of reusing the dredged sediments for beneficial purposes when a TSHD built a sediment trap in the location with the highest sediment concentration and transported the collected sediments to the dewatering units through the pipeline (Koster *et al.*, 2023). During the project, contractors generated a closed-loop dredging cycle adopting different strategies to facilitate clay production in the system, which can later be used for dike reinforcement.

Besseling *et al.* (2021) discussed the beneficial reuse of sediments from the point of view of using dredging equipment by categorizing the whole process into dredging, transport, and application phases. In addition, the circularity aspect of implementing the projects is studied from the perspective of operational costs, emissions, impacts on surrounding natural systems, and the volume of dredged sediments that are being reused. Coulet *et al.* (2014) investigated the possibility of using geotextile tubes as a part of a retaining structure by the Broads authority. Dredging was performed using a grab dredger when using barges for the transport of the dredged sediments. The barges were emptied at the project site by a long-reach excavator, and the sediment was pumped into the geotextile tubes and backfill areas. The dredging contractors conducted a soil investigation before the implementation of the project, and the stages of the implementation of the project were specified. Coulet *et al.* (2016) discussed the use of geotextile bags as a breakwater when dredging the Waterside Marina for maintenance dredging. The breakwater was designed to be stable based on the hydraulic conditions of the estuary and the marina. The sediment was dredged by a backhoe dredger deployed on a pontoon and pumped mechanically into the geotextile bags. The efficiency of the dredging method was continuously monitored during the excavation phase.

The studied literature can be classified as circular port maintenance from the contractor's viewpoint, who aims to justify the dredging processes in a way that can be used for circular projects. Also, integrating regular maintenance dredging with other strategies, such as using sediment traps and sediment pipeline transport, is an interesting topic for contractors. The strategic objective encapsulates all of the circular practices and can be formulated as “*To promote the circularity of port maintenance by optimizing the efficiency of sediment management*”. This objective can be operationalized further by adopting cost and time efficiency factors of the dredging project for contractors, along with the importance of contributing to the circular economy and gaining a reputation in the competitive environment.

PORT AUTHORITIES' PERSPECTIVE

Port authorities consider the dredged sediments as port assets that should be maintained within the port environment, not only to contribute to the circular economy but also to optimize the resource efficiency for construction projects. The final product is achieved when the local environment is preserved and the cost-efficiency of the project is optimized.

A study proposed by H. Hanson *et al.* (2002) discussed national information concerning beach fill operations for coastal protection by reusing dredged sediments from port maintenance. Dean (2003) elaborated on beach nourishment by emphasizing the benefits of these projects, such as damage reduction and environmental enhancement. In another research work, Paipai (2003) and Brandon and Price (2007) investigated different examples of beneficial reuse of sediments, such as reclamation, building construction material, and habitat restoration. Habitat restoration as an application of reusing dredged materials was further analyzed by Yozzo *et al.* (2004), who analyzed the efficiency of using sediments for the construction of artificial reefs, oyster reef restoration, and wildlife island creation. They presented the pros and cons of adopting these strategies along with estimated costs and potential risks of the projects. Studds and Miller (2010) analyzed the reusing of dredged sediments from maintenance dredging for canal stabilization while considering a trade-off between maintaining the accessibility of navigation channels, de-contamination of the sediments, and the suitability of reusing the sediments for construction fill. Other applications of reusing sediments were presented by Temmerman *et al.* (2013), Tonneijck *et al.* (2015), Lunemann *et al.* (2017), and Laperche and Lemiére (2019) on coastal protection, Fuller (2015) and Baptist *et al.* (2019) on tidal marshes enhancement, and Bortali *et al.* (2022) and Nguyen *et al.* (2023b) on building construction material. The Sediment Use as Resource In Circular

And Territorial Economies (SURICATES) project was also another example of nature-based solutions in coastal protection conducted by closed-loop dredging cycles to satisfy the port accessibility requirements and avoid the disturbing of contaminated sediments using a real-time monitoring system (Lemière *et al.*, 2022; Masson *et al.*, 2019).

Coastal erosion was discussed by Pranzini *et al.* (2015) by outlining the major management aspects and the potential strategies that can be used to reuse the dredged sediments for this purpose. Winterwerp *et al.* (2016) described building with nature as an innovative approach to restoring eroding mangrove-mud coasts. They analyzed the patterns of degrading coastlines before the start of the project and adopted sustainable aquaculture policies during the project implementation to prevent soil subsidence, hydrological disturbance, and damage to remaining ecosystems. Then, Pranzini *et al.* (2018) proposed a model that predicts the sediment distribution when being reused in beach nourishment. Nature-based solutions were further discussed by Spearman *et al.* (2022) and Spearman *et al.* (2023) when connecting the potential solutions for habitat restoration and different dredging strategies. They concluded that instead of using TSHDs and discharging material in designated offshore areas, an agitation dredging approach using a Water Injection Dredger (WID) can be adopted to re-mobilize the sediments. This approach reduces the carbon emission and dredging costs significantly and contributes to the circularity by providing the recycling of sediment within the estuarine system. Crocetti *et al.* (2022) and Dengate *et al.* (2022) reviewed the circular trends applied in reusing the contaminated dredged sediments by addressing the technical and socio-environmental aspects of sediment-based by-products. The relationship between sediment management and port maintenance was further developed by Bian *et al.* (2022), who aimed to maximize the amount of sediments being reused and the navigability index in the port that guarantees the port is accessible for a certain period. Later, Sepehri *et al.* (2024b) connected the circular reuse of dredged sediments to different strategies of port maintenance and the efficiency of port processes.

The articles above discuss the circular port maintenance problem from the port authorities' point of view, which can be encapsulated in a strategic objective as "*To promote the circularity of port maintenance by developing practices for reusing the dredged sediments in the port as an asset*". Operationalizing this objective requires multiple considerations, such as determining the physical aspects of the project along with economic and environmental impacts on the local community.

SYNTHESIS

The FoR approach is used to elaborate on how the mentioned strategic objectives could be further operationalized in Table 2.5. The insights obtained from the SLR coupled with the FoR template help us (a) understand the explicit definition of circular practices in port maintenance, and (b) how contractors and port authorities have different perspectives towards these practices. The reviewed studies in the context of circularity show that the majority of articles discuss the challenges of circularity in port maintenance from the viewpoint of port authorities. Most of the studies were focused on different applications of sediment reuse for beneficial purposes such as reclamation, restoration, and building construction materials. These studies view the dredged sediments as port assets that can remain in the port's surrounding environment to contribute to the circular economy. Research on the circularity of port maintenance is rarely developed from the perspective of dredging contractors who focus on closed-loop dredging cycles and altering the equipment design to make it compatible with circular port maintenance operations.

The reviewed studies in the context of circularity show that the majority of articles discuss the challenges of circularity in port maintenance from the viewpoint of port authorities. Most of the studies were focused on different applications of sediment reuse for beneficial purposes such as reclamation, restoration, and building construction materials. These studies view the dredged sediments as port assets that can remain in the port's surrounding environment to contribute to the circular economy. Research on the circularity of port maintenance is rarely developed from the perspective of dredging contractors who focus on closed-loop dredging cycles and altering the equipment design to make it compatible with circular port maintenance operations.

2.4. DISCUSSION

The effectiveness of implementing smart, sustainable, and circular practices in port maintenance is demonstrated in several case studies. Port of Rotterdam (PoR) uses digital tools such as the PortXchange platform to optimize the traffic flow of vessels based on just-in-time arrivals, interactions with other neighboring vessels, and emission reductions (Suvadashini and Dandapat, 2023). Circularity in this port is promoted by defining and implementing land reclamation and habitat restoration projects based on

Table 2.5.: The FoR of circular port maintenance.

Procedure	Contractor perspective	References	Port authority perspective	References
Strategic objective	Promote circularity in port maintenance by increasing efficiency in sediment management.	(Coulet <i>et al.</i> , 2014; Coulet <i>et al.</i> , 2016)	Promote circularity by developing practices that reuse dredged sediments as port assets.	(Bridges <i>et al.</i> , 2018)
Operational objective	Design equipment and processes that achieve the required efficiency for circular sediment management.	–	Preserve port infrastructure and habitats by reusing dredged sediments locally.	(Masson <i>et al.</i> , 2019; Lemièrre <i>et al.</i> , 2022)
Quantitative state concept	Mass of reusable sediment collected over time as a function of hydrodynamics and location.	–	Mass of sediments available as assets for reuse in habitat or infrastructure preservation.	(Nguyen <i>et al.</i> , 2023b)
Benchmarking process	Assess whether closed-loop maintenance operations match equipment performance limitations.	(Besseling <i>et al.</i> , 2021)	Assess whether port infrastructure and habitat preservation performance remain within acceptable limits.	–
Intervention process	Establish closed-loop port maintenance operations aligned with equipment performance limits.	(Koster <i>et al.</i> , 2023)	Define operating limits, balancing economic performance with infrastructure and habitat preservation.	(Baptist <i>et al.</i> , 2019)
Evaluation process	Evaluate how equipment and process redesign enhance sediment management efficiency and circularity.	–	Evaluate how sediment reuse methods improve habitat preservation and support circular port maintenance.	(H. Hanson <i>et al.</i> , 2002)

reusing dredged materials from maintenance (Broussard *et al.*, 2023). Port of Antwerp uses real-time data monitoring systems to optimize the performance of maintenance dredging activities while reducing environmental impacts. Eco-friendly sediment reallocation programs conducted by this port contribute to the circular economy (Van de Keybus *et al.*, 2010). Port of Los Angeles aims to reduce emissions by developing electrified and energy-efficient equipment using alternative fuels. AI and real-time monitoring of air quality and equipment performance help the port achieve a collaborative approach between different stakeholders (Giuliano and Linder, 2014).

Investigating the relevant articles in the context of port maintenance with a detailed exploration of the adopted research objectives and methodologies enabled us to (a) derive literature-based definitions of smartness, sustainability, and circularity in the context of port maintenance, and (b) recognize how different stakeholders may have slightly different perspectives on these themes. SLR revealed several emerging subjects that require additional research, particularly in the area of emission mitigation and the adoption of smart techniques. Future studies can focus on alternative fuels, the electrification of equipment, and carbon capture methods. The key areas of investigation include autonomous dredgers, real-time project data analysis, and predictive maintenance based on the bathymetry patterns. Implementing the proposed approach in real-world projects faces challenges such as technical restrictions, high initial costs, and regulatory constraints. To overcome these barriers, expanding the capacity of infrastructure (terminals, cranes, etc.) and training of experts is required, which can be achieved through pilot projects. Lessons learned from such projects develop an insight into managing costs and risks, developing standardized guidelines, and fostering stakeholder engagement.

The proposed approach in this chapter can be further improved by taking the following considerations into account:

- The SLR approach coupled with FoR used different queries of keywords to search for the most relevant publications for smartness, sustainability, and circularity. However, the size of the obtained publication pools depends on different combinations of keywords. Furthermore, selecting Scopus as the main research dataset could lead to overlooking relevant literature on the subject that is available in Scopus, Scholar, etc. Therefore, the inclusion criterion used in the SLR encompasses the relevant studies that were overlooked in the paper collection stage.
- Both stakeholders in this chapter (dredging contractors and port authorities) are selected due to their greater influence on the regulation of policy and the implementation of operational constraints concerning smartness, sustainability, and circularity. To have a broad viewpoint on the problem, the conflicting interests of all key stakeholders (e.g., port operators, environmental organizations, etc.) should also be included in the analysis.

- Most studies are focused on how processes can be improved from the perspective of different stakeholders to contribute to these three themes. However, the possibility of selecting different strategies for addressing these themes is rarely discussed. For example, the changes in the sustainability aspect of dredging when choosing remobilization instead of reallocation are rarely studied by researchers, while each dredging vessel has its environmental impact (emissions, turbidity, and underwater noise during a project).
- The viewpoints of the contractors and the port authorities on the challenges associated with smartness, sustainability, and circularity are not always contradictory but overlap on some points, which provides opportunities to look for compromises between the parties involved in the project implementation. Clearly stating stakeholders' expectations in the initial phases of a project can help them understand what requirements and limitations need to be considered during project implementation. Defining quantifiable Key Performance Indicator (KPI)s can also help them predict how each strategy highlights the three themes and what innovative solutions can be used for collecting, analyzing, and reporting their data.

Theoretical and managerial insights obtained in this chapter enhance the implementation of smart, sustainable, and circular practices in port maintenance by providing a structured decision-making framework. This framework, which can include the viewpoint of multiple stakeholders, employs the FoR method to clarify and prioritize objectives and metrics used for more informed trade-off quantification. On a practical level, this chapter offers a set of indicators and best practices identified through an SLR, guiding stakeholders in adopting advanced technologies, environmental practices, and circular economy principles.

During the tendering phase or project implementation, the compromise between stakeholders can be adjusted by negotiating clear and quantifiable objectives, metrics, and evaluation measures. The final compromise on strategy selection for port maintenance is achieved through an accurate quantification of different KPIs and comparing the strategies to determine which one fits in each theme. For instance, a smart approach such as data-driven decision-making might suggest the implementation of a strategy that is not sustainable enough. In this case, clearly defining the motivation and requirements of stakeholders can facilitate the decision-making process. There is a need for comprehensive frameworks to effectively incorporate data-driven methods and eco-friendly techniques for reducing greenhouse gas emissions and managing pollutants during dredging. Additionally, practical applications of circular economy concepts, particularly in the reuse and reallocation of dredged materials, are underexplored when contractors address the problem. Along with the results obtained from the descriptive analysis of the final pool of articles that highlighted the scarcity of research in various countries and less attention to certain objectives, a compromise between different stakeholders is lacking when selecting port maintenance strategies.

Quantifying smartness, sustainability, and circularity in port maintenance requires robust methodologies that use measurable indicators and standardized frameworks. For smartness, metrics like the level of automation, data analytics usage, and fuel consumption reductions can be quantified through data-driven approaches. Sustainability can be measured using Environmental Impact Assessments, lifecycle assessments, greenhouse gas emissions, and biodiversity impact. Circularity is quantified through Material Flow Analysis and circular economy metrics, which measure the reuse of dredged materials and resource efficiency. To standardize these methodologies, ports can adopt common frameworks aligned with international standards, use benchmarking tools for performance comparison, engage in collaborative platforms for knowledge sharing, and conduct pilot projects to refine and apply these approaches across different port contexts.

2.5. CONCLUSION

We presented a comprehensive framework to define the concepts of smartness, sustainability, and circularity in port maintenance. An SLR showed to what extent these topics have gained traction in recent years and identified the latest challenges in port maintenance. Next, we showed that different stakeholders, namely contractors and port authorities, can have distinct perspectives on the same themes. This distinction is crucial, as it demonstrates why it is often challenging to agree on these broad and sometimes vaguely defined concepts. By categorizing the studies using a FoR approach, we structured these perspectives to highlight their unique objectives, quantification, actions, and assessments.

The analysis also suggested that despite these different viewpoints, there are notable overlaps in the stakeholders' FoR. For example, both contractors and port authorities recognize the importance of improving process efficiency, albeit from different angles. Recognizing and understanding these overlaps can facilitate better stakeholder collaboration and agreement during project implementation. Finally, our findings suggest

that integrating these different perspectives can lead to innovative approaches in port maintenance. Future research studies can focus on proposing a more accurate quantification of different KPIs on smartness, sustainability, and circularity. Also, including the perspectives of other stakeholders (e.g., port operators, environmental organizations, etc.) provides a holistic approach to addressing smartness, sustainability, and circularity while selecting strategies.

The SLR approach showed the emerging trends in smart, sustainable, and circular port maintenance by descriptively analyzing the authors' contributions from different countries, the number of publications in each year, and the frequency of addressed challenges. Different objectives, metrics, and evaluation measures are used to differentiate the viewpoints of contractors and port authorities toward each of these three themes. A structured FoR framework used in this study offers different stakeholders a clear idea of these concepts and how they can come up with a compromised perspective when selecting port maintenance strategies. This perspective not only incorporates cost and time factors along with these themes but also solves potential conflicts during the tendering phase or project implementation.

New literature-based definitions of smartness, sustainability, and circularity from the perspectives of contractors and port authorities helped us to identify important knowledge gaps for further research. A low number of research articles on circular port maintenance from the viewpoint of contractors is a considerable gap in the corresponding literature. Also, smart port maintenance is rarely addressed from the perspective of port authorities because smartness is mainly implied as a means of improving the efficiency of dredging equipment. Integrating port processes with different scenarios of port maintenance can help ports develop a more comprehensive insight into how this interference can be quantified.

Integrating perspectives from stakeholders can be effectively managed through structured engagement, transparent communication, and collaborative decision-making. To do so, tools such as MCDA can be used to balance different interests and form stakeholder advisory committees for consultation. Digital collaboration platforms can facilitate real-time data sharing and feedback, while public-private partnerships encourage joint decision-making and shared investment. Future research could explore the socio-economic implications of port maintenance strategies, such as potential job creation and broader impact on local communities. Involving more stakeholders, such as terminal operators and environmental organizations, helps accurately quantify more trade-offs. Anticipated changes in the FoR approach include real-time decision-making for different phases of projects and expanding stakeholder engagement mechanisms to maintain the relevancy and alignment of decision-making during the process.

3

SMART PORT MAINTENANCE

The whole is other than the sum of its parts.

Kurt Koffka

This chapter addresses "Sub-question 2: How can smart, data-driven methods quantify the interaction between seagoing processes and maintenance dredging?" by developing a data-driven methodology to quantify interactions between maintenance dredging activities and seagoing navigation processes, thereby operationalizing smartness in port maintenance. The methodology combines Automatic Identification System (AIS) data from both dredging vessels and commercial shipping with spatial-temporal analysis techniques. Vessel movements are structured into event tables, allowing dredging operations and seagoing traffic to be analyzed consistently at multiple scales, ranging from individual encounters to system-wide traffic patterns.

A case study at the Port of Rotterdam is used to demonstrate the approach. AIS data are analyzed to identify spatial and temporal overlap between dredging zones and navigation routes, as well as temporal overlap with vessel arrivals and departures. The results reveal distinct interference patterns, including localized conflicts near berth areas and access channels. The analysis shows that even small-scale dredging operations can influence port accessibility beyond their immediate footprint.

The chapter concludes that smartness in port maintenance is not limited to automation or real-time control, but fundamentally concerns the ability to use AIS data to make system-level interactions transparent and measurable. The proposed method provides a quantitative basis for identifying planning opportunities that reduce interference with port processes, supporting smarter scheduling and coordination without prescribing a single optimal solution.

This chapter is based on a published research paper:

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3.1. INTRODUCTION

Smart practices in port maintenance could be defined as using data-driven methods to improve the efficiency of dredging and seagoing activities and satisfy existing requirements for different stakeholders. Among the various challenges arising from maintenance dredging is the precise planning of dredging operations in high-traffic areas, which refers to sections of the port characterized by a significant volume of vessels (80–90 deep-draft vessels per day). Areas such as navigation channels, berths, and terminal facilities frequented by large container vessels, tankers, and bulk carriers experience notably dense maritime traffic, making it more challenging for ports to adjust traffic flows and minimize delays. Therefore, optimizing berth allocation becomes critical when berth areas need maintenance, considering operational costs and environmental impacts. The problem of berth allocation has been investigated in previous research works; however, this problem is rarely addressed when analyzed along with port maintenance.

Optimizing berth occupancy is addressed in a study by G. Tang *et al.* (2016), who investigated the potential of developing a just-in-time scheme for arrivals and departures to minimize the total duration of a vessel's stay in the port area (i.e. turnaround time). In another study by Jahn and Scheidweiler (2018), a forecasting model is presented based on historical AIS data of the vessels to estimate the arrival time of the vessels. Optimizing berth allocation may also have other incentives, such as minimizing potential emissions across the port system (Merkel *et al.*, 2022). In this context, Poulsen and Sampson (2020) conducted a study using empirical data from port calls and analyzed the impact of the idle time of the ships on total emissions. To quantify these interactions, Y. Xu *et al.* (2018) discussed how the lack of nautical accessibility affects berth planning. They proposed a mixed-integer linear programming model to formulate the berth planning problem, and then analyzed three cases assuming that the berth is built based on one-way traffic, bidirectional traffic, and temporary closure due to lack of nautical accessibility. In another study by Souf-Aljen *et al.* (2016), the interference between dredging and port operations is discussed by analyzing the waiting time for seagoing vessels caused by a Grab Dredger (GD) when it performs dredging operations near the quay walls.

In a study proposed by Cheng *et al.* (2019), AIS data is used to track the movements of dredgers and detect anomalies in their navigation. The data set collected is used in an online platform that estimates anomalies and predicts possible interactions with other vessels in a given region. This analysis is done by developing probabilistic models based on historical dredging trajectories. Another study on dredging trajectories is proposed by Bokuniewicz and Jang (2018), who visualized heat maps showing the highest intensity of dredger presence in specific areas. They then use these heat maps to present a scheme for the sustainability of sand reserves in the port. Other data-driven methods are used in dredging operations using simulators for crew training, developing morphological models using machine learning, using big data for strategic planning of dredging operations, and automatically controlling equipment (Bashir, 2022). Yen *et al.* (2023) investigated the interactive relationship between port authorities and contractors through the sharing of real-time data, focusing on interference between maritime and dredging operations. The study highlights the importance of data-driven methods for improving communication and collaboration between the various parties involved in port maintenance.

Conventional methods have mainly focused on the design phase of bed levels, overlooking the crucial interaction between nautical accessibility, maintenance dredging strategies, and port process performance. On the other hand, a study assessing port processes and maintenance dredging activities using AIS data analysis is lacking in the corresponding literature. This study aims to fill this research gap by filtering and analyzing the AIS data of two cases of maintenance dredging in Mississippihaven in the Port of Rotterdam (PoR) using Trailing Suction Hopper Dredger (TSHD) as the main dredging vessel. In one case, planning is done so that a dry bulk vessel can be served in the terminal together with a TSHD vessel, and the other case shows a delay in navigating to the berth area during maintenance dredging. This process is repeated for similar periods to determine the delays experienced by vessels due to their interference with maintenance dredging operations. The results of the analysis of the AIS data trajectories are then presented, and theoretical and managerial implications are drawn.

This chapter uses big data analysis in Section 3.2 to track the interaction between maintenance dredging and seagoing processes. It determines the total waiting periods of dry bulk vessels caused by berth hindrance. Substantial historical data on vessel movements is analyzed to cover the traffic density in Mississippihaven during 2019. This data is coupled with operational data from port operations, including vessel schedules, berth occupancies, and navigation channels' utilization. The final dataset includes the movement of dry bulk vessels operated in the terminal and the dredging cycles of TSHDs conducting maintenance dredging. In total, 250 files of vessel data (real-time location of movements) are obtained for the initial analysis after filtering the datasets based on vessel types and vessels operating in the terminal. To simplify the problem and focus on the representation of these interferences, this study analyzes a limited time window and a certain

amount of AIS data in Section 3.3 to illustrate the waiting times. After identifying the waiting times, theoretical and managerial implications of this analysis are proposed, and solutions to the emerging challenges are recommended. Future research directions are also discussed in Section 3.4 when addressing these challenges from both the port authority and the dredging contractor perspectives. Finally, Section 3.5 concludes the findings.

3.2. METHOD

The PoR is responsible for the maintenance of port basins. The research uses data from the AIS to analyze vessel movements in the Mississippihaven. The AIS data is accessed through the PoR's Application Programming Interface, and the dataset is analyzed on the Microsoft Planetary Computer platform. This platform provides a robust environment for processing large-scale geospatial data and enables efficient analysis of vessel movements and interactions.

The available AIS data provides insight into the presence of vessels in the PoR in 2019, and capturing snapshots of a vessel's locations shows its movement and interaction with other elements of the system. Due to the high traffic of different vessels in Mississippihaven, this terminal was selected as a case study to analyze how seagoing and dredging vessels interact. Maintenance dredging at this terminal is mainly conducted by TSHDs. These vessels load sediments from the berth area and unload them in the designated discharging area at Loswal. During maintenance dredging, the berth is occasionally closed, or access to the berth is restricted as the large TSHDs have to use the entire area for dredging.

To identify maintenance dredging in Mississippihaven, the vessel type is limited to dredging vessels. Then, it is determined if the vessel was present at both the terminal and the discharging location. This filtering ensures that the dredging vessel is a TSHD performing maintenance dredging, while other capital dredging operations, such as deepening or reclamation, could be performed by a TSHD where the vessel is not discharging sediments at the discharging area. Monitoring the vessel's movements and examining its interaction with dry bulk vessels provides insight into the length of time seagoing vessels spend waiting before entering the terminal. Moreover, the overall length, which is the maximum length of the vessel from its foremost point to its aftermost point, is considered a crucial measurement in assessing the size and capacity of dry bulk vessels during the analysis of port processes. The maximum draft, which denotes the deepest point of the vessel's hull submerged below the waterline, is also another attribute of the analyzed AIS data, which shows the navigational and cargo handling capacities of dry bulk vessels.

A flow chart to process the AIS data shown in Figure 3.1 provides a visual representation of the steps used to extract the target dataset and determine the interaction between the seagoing and dredging processes. This flowchart guides the study through the key stages, including selecting the geographic region of interest, delineating specific timestamps within the selected time window, and identifying the intersections between seagoing and dredging vessels. Together, these steps help to capture the dynamics of vessel interactions in the designated port area. By tracking ship movements based on potential interaction periods, the waiting time of bulk carriers can be measured.

The area of interest is selected based on the highest number of vessel movements and possible interferences observed between vessels during one year. The temporal limitation allows for a targeted study of vessel movements during a certain time, which enables a differentiated analysis of the dynamics in the terminal. The nautical guaranteed depth, which is the water depth required to ensure the safe navigation of vessels, is 23 m for Mississippihaven, which shows the large draft of dry bulk vessels being served in this terminal. After filtering the vessel types and required time slots for vessels' navigation, the movement of vessels and their interferences are shown in separate Gantt charts.

3.3. RESULTS

3.3.1. CASE STUDY

By analyzing the AIS data in the Mississippihaven terminal, a total of 11420 trips were identified (see Figure 3.2a). The trips were accurately filtered to determine the interaction of TSHDs with dry bulk carriers. To ensure the accuracy of the analysis, separate polygons are used for both the terminal and the discharging areas, excluding data consisting of vessels passing through both regions and, in particular, TSHDs carrying out dredging operations. Five TSHDs are identified by filtering the dredgers that are in the terminal and discharging area. The trajectory on which these vessels travel back and forth is shown in Figure 3.2b.

Since some of the seagoing vessels used the Mississippihaven to access other terminals, a narrower area is filtered to represent the areas closer to the berths for unloading bulk cargoes. Two scenarios are then examined:

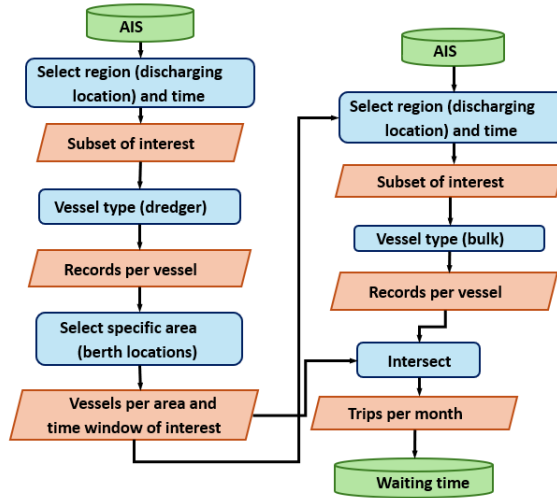


Figure 3.1.: AIS data analysis flow.



Figure 3.2.: Traffic intensity of (a) all vessels and (b) TSHDs movements between Mississippihaven and the Loswal (discharging area).

Scenario 1 shows no interference between maintenance dredging and seagoing processes, and in Scenario 2, the seagoing vessel experiences a waiting time due to maintenance dredging.

3.3.2. SCENARIO 1. NO INTERFERENCE

Five TSHDs are identified, and the interaction between these vessels and bulk carriers served at the terminal is analyzed during the periods when the TSHDs were operating at the terminal. In this scenario, the movement of a TSHD with a dry bulk carrier is analyzed when maintenance dredging does not cause delay for the dry bulk carrier before it is served in the terminal. The interaction of two dry bulk carriers with a TSHD on 29 and 30 July 2019 is analyzed to determine a possible waiting time for one of these vessels. Figure 3.3 shows the exact timestamp of the dredging and seagoing processes on these two days to give a visual representation of the problem. These vessels are used as examples of interference, while other seagoing vessels were operating in the area at the same time.

In the early hours of 29 July 2019, TSHD1 begins its first loading cycle, extracting sediments from the harbor. After TSHD1 finishes its dredging cycle, dry bulk vessel 1 arrives in the berth and goes directly to the quay wall for cargo unloading. During the unloading process, TSHD2 performs another cycle in the middle area of the terminal, as there is enough space to load sediments for the dredger. The dry bulk vessel 1 and TSHD1 then leave the area at the same time without experiencing any waiting time. During the next day, dry bulk vessel 2 arrives at the terminal to unload the cargo, and during cargo handling, TSHD1 conducts another maintenance dredging cycle. In this scenario, TSHD1 leaves the area more than one hour earlier than dry bulk vessel 2. In

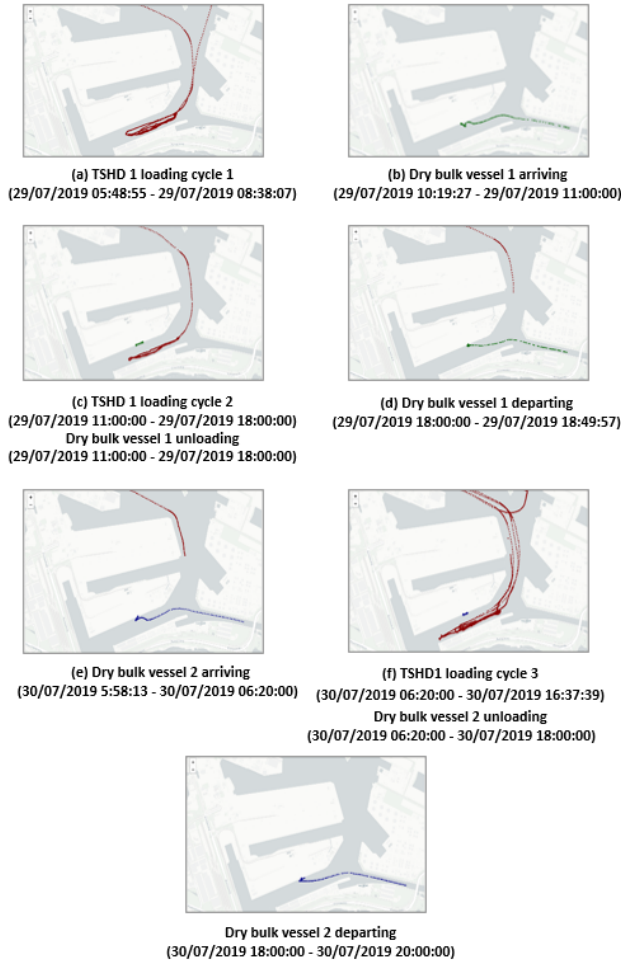


Figure 3.3.: Results obtained from AIS trajectories to visualize the interference between seagoing (green trajectory for dry bulk vessel 1 and blue trajectory for dry bulk vessel 2) and dredging (red trajectory) processes.

total, three different maintenance dredging cycles are performed by the TSHD1, and no interference in terms of waiting time is observed for the seagoing vessels. It happened mainly because of the precise scheduling of vessels before being served in the terminal and enough nautical depth for the navigation of dry bulk vessels when departing from the quay wall.

3.3.3. SCENARIO 2. INTERFERENCE

Refining the dataset to focus exclusively on vessels handling cargo at the dry bulk berth on the north side of the terminal reveals interesting patterns. The analysis shows that 57 trips were made by 10 different seagoing vessels along the quay wall. In particular, consecutive cycles of the identified TSHDs were identified in the period from 17 to 19 July 2019. Consequently, the interference between TSHD2 and seagoing vessels during this period will be studied in detail, including some days of extension at the beginning and at the end. The processes of dredging and dry bulk navigation are summarized in Figure 3.4, where the maintenance dredging performed by the TSHD2 is shown in red on the right panels, and the seagoing processes are shown in green

on the left panels.

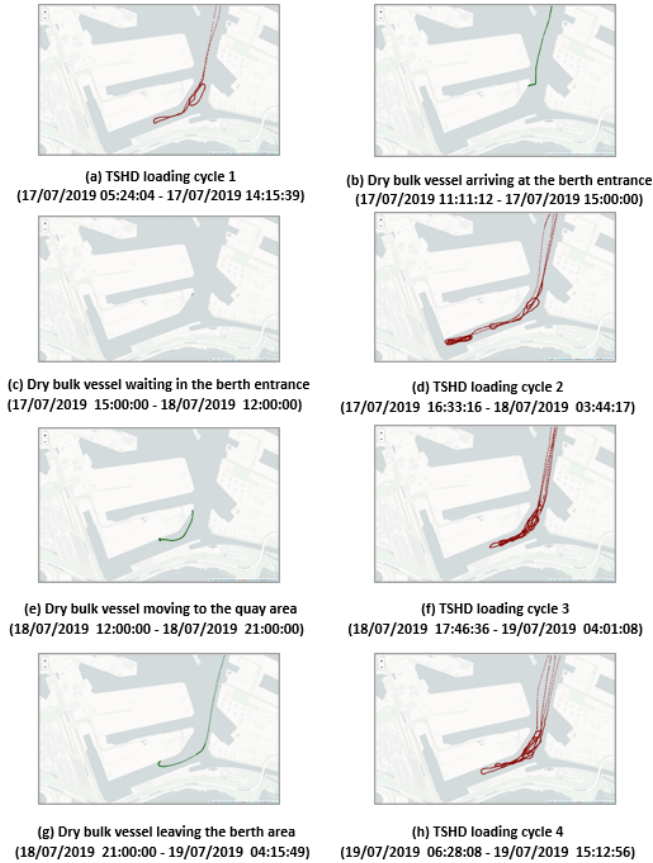


Figure 3.4.: Results obtained from AIS trajectories to visualize the interference between seagoing (green trajectory) and dredging (red trajectory) processes.

In the early hours of 17 July 2019, TSHD2 initiates its first loading cycle, during which sediments are removed from the port. At the same time, a dry bulk carrier 3 arrives at the port entrance. As TSHD2 loads sediments, the dry bulk carrier waits at the port entrance, following precise maritime protocols. This wait continues until midday on 18 July 2019, when the dry bulk carrier 3 finally receives clearance to approach the quay area for cargo handling operations. While the dry bulk carrier 3 completes its operations, TSHD2 carries out further loading cycles on the 17th and 18th of July, each carefully planned to ensure the navigability of the port. The vessels lie side by side in this area. On the morning of the 19th of July 2019, as dry bulk carrier 3 leaves the berth area, TSHD2 begins its fourth loading cycle. This sequential analysis of timestamps enables a differentiated understanding of the interaction between maintenance dredging and seagoing vessels.

The interference between maintenance dredging and seagoing vessels, analyzed using AIS data, shows that several factors, such as berth capacity, nautical depth, sailing speed, and hopper capacity, are important. A holistic consideration of these factors provides both contractors and port authorities with a comprehensive perspective and facilitates the identification of solutions to minimize waiting times. The different processes of dredgers and dry bulk carriers in both scenarios are summarized in Figure 3.5.

In the first scenario, the vessels operated without any disruption. In addition, three maintenance dredging cycles are carried out by the TSHD1, which ensures sufficient nautical accessibility for dry bulk carriers passing through the terminal area. The potential interference between TSHD1 and two dry bulk carriers over two days

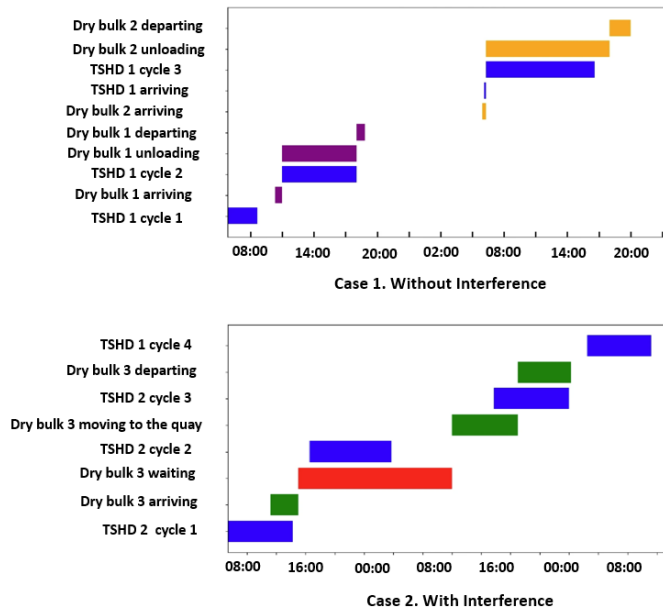


Figure 3.5.: Gantt chart showing the daily illustration of different processes using AIS data.

is analyzed to ensure that the dredging operations do not cause any interference (see Figure 3.5a).

The waiting time for dry bulk carriers at the port entrance is too long (21 h) in the second scenario (shown in red color), which shows the lack of nautical accessibility before the dredging works and the lack of unloading infrastructure in the terminal (see Figure 3.5b). The observed disruption underlines the central role of careful planning of the dredging operations to significantly reduce delays.

3.4. DISCUSSION

Analyzing the interactions between maintenance dredging and seagoing processes leads to suggesting substantial implications for port maintenance strategies. Predominantly conducted by TSHDs, maintenance activities often lead to temporary berth closures due to the substantial space required for maneuvering during sediment loading. This limitation prompts consideration of alternative equipment, such as Water Injection Dredger (WID)s, which are smaller equipment used for maintenance dredging. Due to their size and higher maneuverability, these vessels can access areas close to quay walls that are more challenging to dredge by TSHDs. Moreover, stationary equipment such as Back Hoe Dredger (BHD)s and GDs are less intrusive alternatives, particularly when used in tandem with barges for sediment reallocation.

Different stakeholders might have contradicting viewpoints on the problem. Port authorities aim to minimize the waiting time for seagoing vessels, as any idle time might cause penalty costs for ports and decrease the efficiency of cargo handling processes. Also, they aim to maintain nautical accessibility to guarantee the safe navigation of large-draft vessels. On the other hand, dredging companies focus on increasing the efficiency of their processes by decreasing the length of dredging cycles and minimizing the vessels' idle times. This contradictory approach can be broadened in terms of implementing different maintenance dredging strategies and quantifying different key performance indicators.

Data availability is limited to four months of 2019, restricting the number of maintenance dredging cycles conducted in Mississippihaven. The analysis done in this study showed that only one TSHD was performed in July 2019, and found that its interactions with seagoing vessels occurred in two days. Also, determining these interactions needs an accurate analysis of the vessels' movement in short time slots to visualize the movements of these vessels. The main purpose of the performed analysis is to quantify the trade-offs between different criteria, such as time needed to finish the maintenance dredging, operational costs, environmental impacts of

dredging activities, and utilizing alternative equipment and strategies for port maintenance. However, the AIS data provides us with limited anonymous information on the vessel properties, and any further data needs to be requested separately from the port authorities. In the case of quantifying the trade-offs, more information about the dredging equipment also needs to be obtained from dredging contractors.

Analyzing AIS data in this study helped identify the interactions between dredging and seagoing operations; however, these interactions are not usually identifiable. It happens because many of the delays occur because of other reasons, such as lack of berth availability, high congestion in the terminal, and lack of available port operators (tugboat, pilot, etc.). Even with obtaining some more information about the vessel types and observing the trajectories of vessels from each type, the best way of quantifying the interactions is to ask port authorities that have an integrated system of vessel logs. The increasing availability of AIS data can provide more detailed information about the trade statistics for each port infrastructure and determine the trade flows in each port zone. Navigation performance can also be measured using AIS data, while vessels should follow a specific route before being served in terminals, and any deviation can have cascading effects on other port processes. Using AIS data is still expanding its impact from seagoing navigation to inland navigation, which is a novel approach for both public and private sectors to facilitate the transportation of products between cities.

The future trajectory of research in this domain can be evolved through AIS data utilization. Simulating dredging operations and port processes concurrently emerges as a promising avenue for exploration. Such simulations empower port authorities and contractors to forecast and proactively reschedule dredging activities in response to fluctuations in port traffic. Optimizing operational parameters for dredging vessels, encompassing speed and loading rate adjustments, stands out as a potential strategy to minimize waiting times for seagoing vessels. The increasing availability of AIS data can be harnessed to provide detailed trade statistics, assess navigation performance, and determine trade flows in specific port zones.

Additionally, exploring the impact of AIS data on mitigating environmental consequences and enhancing the overall sustainability of port operations needs more attention. As the integration of AIS data continues to grow, its potential to revolutionize strategic planning in dredging operations and enhance overall navigation efficiency remains an exciting prospect for future investigations. Simulating the dredging operations and port processes allows both port authorities and contractors to predict the upcoming port traffic and prepare to reschedule the dredging process. The waiting time that poses penalty costs for port authorities can be minimized by making maintenance dredging activities just-in-time. Moreover, changing the operational parameters of dredging vessels (speed, loading rate, etc.) can regulate the activities in a way that leads to reducing seagoing waiting times.

3.5. CONCLUSION

In this study, the interaction between dredging and seagoing vessels in the Mississippihaven (PoR) is investigated. These interactions are quantified as waiting times experienced by the vessels due to a lack of sufficient nautical depth at berth. For this purpose, the time frame is limited, and vessel movements are monitored within this time frame. After identifying the waiting times, the port authorities confirmed that these were due to the ongoing maintenance dredging work.

A new data-driven approach was developed to analyze the interaction between dredging and seagoing vessels. The AIS data collected from the port authority was analyzed to identify the TSHDs that were conducting maintenance dredging in the terminal and to monitor their impact on the navigation of other vessels. To narrow the analysis, the time frame was limited to a single month of available data in 2019, and the interaction of vessels was examined for a single berth. It was found that a dry bulk carrier had to wait at the terminal entrance before being served at the berth because a TSHD was dredging the entire terminal. Subsequently, this interaction was analyzed in a Gantt chart, and solutions were proposed to minimize the waiting time. Finally, the implications and limitations of this study were discussed, and future research directions were recommended.

Industry practitioners can use the analysis proposed in this study to consider the interaction of dredging and seagoing processes in the tendering phase before the project is implemented. During the tendering process, a precise prediction of the number of delays helps both port authorities and contractors to compromise on the selection of different strategies. Moreover, minimizing the waiting times due to a lack of nautical accessibility helps port authorities to facilitate the port processes and contractors to select dredging strategies. It will also be useful for the selection of alternative dredging equipment for maintenance dredging projects to reduce disruption and minimize the time and cost required for the project.

In addition, other aspects of maintenance dredging projects, such as sustainability (environmental impact on the marine ecosystem, emission reduction, etc.) and circular economy (beneficial reuse of dredged

sediments), can be defined, quantified, and applied based on the aforementioned interactions. According to the significance of each aspect for each stakeholder, the selected strategy varies in comparison to the case where selecting the strategy is only based on the lower cost of dredging.

4

SUSTAINABLE PORT MAINTENANCE

Truly successful decision-making relies on a balance between deliberate and instinctive thinking.

Malcolm Gladwell

*This chapter addresses **Sub-question 3: How can the sustainability impacts of maintenance dredging equipment selection be quantified?** by developing a physics-based, discrete-event simulation framework to quantify the sustainability performance of maintenance dredging strategies, with a focus on CO₂ emissions. The methodology integrates hydrodynamic resistance formulations, sediment characteristics, vessel propulsion power, and dredging equipment loads into a coherent emission estimation model. Maintenance dredging operations are decomposed into discrete phases, such as sailing empty, dredging, sailing full, and discharge, which are represented in event tables to enable transparent attribution of energy use and emissions.*

Two scenarios are analyzed for a case study of the Port of Ramsgate: a Trailing Suction Hopper Dredger (TSHD) and a Water Injection Dredger (WID) operating under representative port maintenance conditions. The results show that emissions per spatial area differ markedly between vessel types and operational phases. For the TSHD, sailing phases dominate total emissions, whereas for the WID, jetting and pumping activities play a more prominent role. The analysis further demonstrates that emission intensity does not scale linearly with production or project duration, revealing trade-offs between speed, efficiency, and environmental performance.

The chapter concludes that sustainability assessment requires phase-specific and process-level analysis. By explicitly linking emissions to operational decisions and project duration, the proposed framework provides a robust basis for comparing dredging strategies and evaluating sustainability trade-offs in future maintenance planning.

This chapter is based on a published research paper:

A. Sepehri, A. Kirichek, M. Van den Heuvel, M. de Geus, and M. Van Koningsveld (2026). "Sustainable port maintenance: dredging equipment selection in time-emission trade-offs". In: *Results in Engineering*, p. 109247. DOI: 10.1016/j.rineng.2026.109247

4.1. INTRODUCTION

Port maintenance is increasingly guided by sustainability as well as cost and time. Sustainable port maintenance aims to protect the environment and community by reducing adverse impacts like water turbidity, emissions, and underwater noise. This requires choosing equipment and methods that minimize dredging frequency and emissions, reflecting a more holistic approach that integrates economic, environmental, and social goals (Sepehri *et al.*, 2024a). Concerning the reduction in port maintenance emissions, the International Maritime Organization (IMO) set an ambition to decrease emissions in the maritime sector by 50% in 2050 (IMO, 2023). Although dredging activities account for 0.6% of maritime emissions, their impact is significant due to the increasing number of port development projects and the growing need for maintenance dredging (Van de Ketterij *et al.*, 2009). A variety of studies have investigated the emissions of dredging equipment. They can be divided into studies on exhaust emission reduction policies, conceptual and empirical frameworks, and quantitative methods. Focusing on TSHDs and WIDs as the most commonly used equipment in port maintenance, emission estimation as a function of space and time during a project is lacking in the corresponding literature, while project-specific input, vessel characteristics, and sediment properties influence the outcome.

Laboryrie *et al.* (2018) presented a generic framework for estimating greenhouse gas emissions from dredging equipment, based on vessel type and operational activities. However, the framework lacks detail on the power consumption of individual vessel components and how these contribute to overall emission estimates. The study relies on empirical data collected from the dredging industry and provides general indications of CO₂ emissions per in-situ cubic meter of removed sediment for five TSHD size classes and three standard operational cycles: placement using bottom doors, placement via 1 km onshore pumping, and placement through rainbowing. While these aggregated figures offer useful benchmarks, they are based on a standardized scenario involving a fixed sailing distance of 10 nautical miles (approximately 18.5 km), limiting their applicability to projects with different characteristics, such as varying sailing or pumping distances. As a result, the framework cannot be easily applied to diverse project types or vessel configurations, nor does it offer a reusable model that incorporates real-world input for broader applicability.

Slamet *et al.* (2020) examined the greenhouse gas emissions produced by TSHDs used in supplying sand for large-scale coastal land reclamation projects in Indonesia, with a focus on the Jakarta Bay development. As the country plans to reclaim vast coastal areas, requiring up to 109 million m³ of sand for just one project, dredging emissions become a significant yet under-reported environmental concern. The authors simulate emissions across four operational phases of TSHDs and find that sailing contributes the most (37–55%) to total emissions, especially over long transport distances between quarries and reclamation sites. While reducing vessel speed lowers emissions, it also increases project duration. The study underscores the need to include dredging activities in national carbon accounting and provides insights into how operational strategies and vessel selection can affect the environmental footprint of reclamation efforts. Emissions are estimated based on speed-power proportions from maximum engine capacities per dredging phase and the number of dredging cycles executed by the vessel. However, the interaction between the vessel, sediment, and water is not investigated, limiting the accuracy and applicability of the emission estimates.

C. de Roode *et al.* (2022) developed an emission model for TSHDs, detailing CO₂, SO_x, and NO_x emissions across six operational phases. Validated with real job data, the model identifies key emission sources and fuel use per dredged cubic meter. It also evaluates five reduction strategies: using mechanical power arrangements (especially combined drive), controllable pitch propellers, optimizing trailing speed, installing closed-loop scrubbers, and shutting down idle engines. The model helps predict emissions and improve operational efficiency across various TSHDs, assuming the vessel's total power consumption is a proportion of the total installed power. Even though this study validates emissions during TSHD operation and explores reduction strategies, it simplifies real-world conditions by not accounting for variations due to changes in project specifications and only focusing on a certain vessel.

Emissions of a WID are only studied based on empirical data received from port authorities, and the majority of research works are primarily focused on analyzing the working method and assessing the production of vessels in real-world cases. Kirichek and Rutgers (2020) investigated the effectiveness of WID as an alternative to traditional maintenance dredging with a TSHD. A pilot project was conducted in the Port of Rotterdam, where a WID was used to fluidize and remobilize sediments to monitor the settling and consolidation of the fluidized sediment, evaluate nautical depth using density and yield stress criteria, and compare historical dredged volumes and CO₂ emissions with previous TSHD maintenance. The results demonstrate that WID can significantly reduce maintenance frequency, dredged volumes, and associated emissions. However, the study did not provide a methodology for quantifying these benefits in advance.

A few research studies provide a more detailed analysis of emissions for dredging equipment. For instance,

Van der Bilt (2019) used a discrete-event simulation approach that allows control over activity parameters (e.g., duration, total dredged volume) and vessel properties (e.g., trailing speed, hopper capacity). When coupled with physics-based models, the simulation enables more precise emission estimates for sailing stages (Lamers, 2022) and loading/unloading stages (Janssen, 2023). These models account for energy consumption by key components such as the propulsion system, inboard dredge pumps, jet pumps, bow thrusters, and onboard electrical systems. Additionally, they provide a production estimation tool that links emissions to the dredger's operational efficiency. The same calculations were investigated by Prins (2024) to estimate the production rate and emission estimates of a WID. However, a systematic approach to quantitatively compare the performance of different work methods on a range of parameters appears to be lacking in the open literature (de Boer *et al.*, 2023b).

Existing emission estimation methods for dredging oversimplify real-world conditions and lack adaptability to varying equipment and project characteristics. This chapter addresses this gap by introducing a framework to systematically quantify energy use and exhaust emissions associated with dredging activities. By combining physics-based and data-driven methods, the framework accounts for key variables such as vessel characteristics, project specifications, and sediment properties. This enables more accurate comparisons between different dredging equipment and supports effective emission-reduction strategies. The framework presented in Section 4.2 supports multi-perspective analysis and helps formulate the problem, and outlines some key modeling decisions. Section 4.3 applies this framework to analyze dredging activities, and 4.4 summarizes the findings and outlines future research directions.

4.2. METHOD

4.2.1. CONCEPTUAL MODELING OF EMISSION ESTIMATION IN PORT MAINTENANCE

To accurately estimate emissions of TSHDs and WIDs, real-world conditions, including vessel specifications, water characteristics, and soil properties, need to be taken into account. The main challenge is to address the complexities of emission estimation for both TSHD and WID vessels, considering their underlying activities and factors causing the emissions. To do so, we need to know the sequence of activities performed by vessels in a project and select physics-based models to assess the interaction of vessels with the surrounding environment.

de Boer *et al.* (2023b) suggested discrete-event simulation as a method to specify dredging activities and quantify how multiple such activities in a sequence translate to performance indicators such as production, project duration, and emissions. They used an open Python library called "OpenCLSim" to analyze the sailing, loading, and unloading of multiple vessels within different geographical locations. The start and stop times of activities are drawn as the outcome of the simulation, and the changes in the level of sediment in different locations can be determined. We implemented the framework using version 1.6.1 of OpenCLSim (de Boer *et al.*, 2023a) to formulate a simulation model for a case study in which WID and TSHD vessels can be selected to complete a given project.

The simulation is coupled with physics-based models to estimate vessels' power requirements, the associated energy consumption, and subsequent emissions during each activity. The physics-based models incorporate vessel and project specifications to analyze the total emissions and duration in a real-world environment. Total emissions of a dredging vessel EM_T per tons of fuel consumed are estimated based on its total energy consumption E_T and the characteristics of the fuel used.

$$EM_T = E_T \times SFC \times EF \quad (4.1)$$

Each fuel type has a specific fuel consumption SFC and an emission factor EF per exhaust pollutant type. The total energy consumption E_T is estimated by integrating the power demand of individual vessel components P_x over their operational duration dt . Each component's power use is computed using its physical specifications and the resistance it must overcome in interaction with the environment. This estimate is constrained by the maximum power installed (Holtrop and Mennen, 1982; Janssen, 2023; Miedema *et al.*, 2007):

$$E_T = \int P_x dt \quad (4.2)$$

The power required for different dredging activities is allocated to pumps, propulsion systems, bow thrusters, and the onboard power network of the vessel. Pump power is used mainly for fluidizing and transporting sediment, while propulsion power is needed to overcome the resistance of the hull of the vessel and dredging-related appendages. Bow thruster and net power onboard are kept as constant terms for

simplicity. When estimating the project duration for WID, the distance between the dredging site and the port entrance is a critical factor. Details of power consumption and operational duration are summarized in Appendix A and Appendix B, respectively.

To account for this, the port area can be divided into zones based on two hydrodynamic regimes: High Energy Environment (HEE) near the port entrance, where strong tidal currents assist sediment dispersion, and Low Energy Environment (LEE) further inside the port, where weaker currents make sediment transport more challenging. In LEE areas, the greater distance to open water increases the likelihood of early settling or partial transport back into the basin due to tidal reversals. Therefore, WID operations in these zones must be carefully aligned with tidal cycles, creating tidal working windows that affect operational planning and efficiency. In contrast, maintenance dredging activities performed by a TSHD are not affected by this categorization and are mainly dependent on their operational phases (C. de Roode *et al.*, 2022). Although TSHDs and WIDs employ fundamentally different dredging methods, applying the concept of energy footprint per activity allows us to directly compare their overall performance and pinpoint the underlying causes of variations. By quantifying the duration and emissions across multiple strategies, stakeholders can then identify the most suitable fleet configuration for their goals, whether prioritizing project time or environmental footprint (Van Koningsveld *et al.*, 2023). Finally, estimated durations and emissions for the WID are validated against vessel and activity logs to ensure accuracy.

4

4.2.2. DESIGNING AN EVENT TABLE FOR MULTI-PERSPECTIVE EMISSION ESTIMATION

Once the vessel and project requirements are clear, a systematic quantification method is needed that allows analysts to explore the problem from different perspectives without repeated iterations. Analyzing individual work methods can be done using a multi-perspective approach, allowing for zooming in and out in time and space, comparing the work methods in overall patterns and detailed causes of emissions. To achieve this, we adopt the “event table” concept developed by Van der Werff *et al.* (2025), which is particularly relevant for this study due to its ability to link large-scale emission patterns to localized vessel behavior and environmental conditions through a multi-perspective systems framework. Their approach addresses key challenges identified in the literature, such as the need to account for spatial and temporal variability, diverse operational profiles, and local environmental influences, making it highly suitable for structured emission evaluation in complex port maintenance operations. The event table, inspired by the concepts of agents (site, vessel) and event logs, allows for keeping track of the agent's properties during a certain period when filtering and aggregating operations are performed on the required data.

The event table serves as a structured data framework that connects vessel activities with their spatiotemporal context and contributing factors, enabling both detailed and aggregated analysis. It is organized around four core perspectives: **scales**, which define the spatial and temporal scope of dredging operations; **conditions**, which reflect environmental and vessel-specific factors affecting emissions; **behavior**, which captures the sequence and influence of vessel activities; and **dependencies**, which outline interrelations and constraints between activities. Table 4.1 presents how each perspective translates into specific data and analytical requirements for emission estimation in the context of port maintenance dredging.

Table 4.2 provides a more detailed description of the objectives for the port maintenance dredging case, along with the specified requirements for the data that will be incorporated in the event table.

SCALES

To understand to what extent this analysis allows us to zoom in on the project and how we can link the details of the project to activities, the scale perspective helps in defining where and when activities occur, establishing the spatial and temporal boundaries of a dredging project. We take the Port of Ramsgate as the case study, where regular maintenance dredging is needed to maintain a minimum depth of 7.5 meters in the entrance channel and 7 meters in the berth area. We incorporate hydrographic survey data that shows a total of 135000 m³ of sediment available for dredging. A WID is available to start dredging on 16 June 2024, starting from zones closest to the port entrance (HEE) and proceeding inward (LEE) (see Figure 4.1a). To have a more accurate estimation of dredging productivity, the whole dredged area is divided into four sections based on their centroid distance to the HEE to demonstrate how the details on the time needed to finish dredging are reflected based on this differentiation.

A hypothetical case is defined when a TSHD performs activities based on three scale specifications of loading, unloading, and sailing to conduct a vessel-activity-timestamp event (see Figure 4.1b). The total dredging cycle duration is dependent on hopper volume, dredging and sailing speeds, and production rate. Assuming that there is no large difference in water depth over the sailing route, it is deemed acceptable to

Table 4.1.: Perspectives for emission estimation in port maintenance dredging.

Perspective	Focus	Purpose	Key data requirements
Scales (The 'where' and 'when' of dredging operations)	Spatial-temporal scope	Define project boundaries and locate dredging activity in time and space	Project area characteristics Dredging duration and timing Vessel movement patterns Dredging cycle segmentation
Conditions (Environmental and vessel-specific factors)	Emission influencers	Assess how physical and operational characteristics affect emissions	Seabed and soil composition Water depth
Behaviors (Operational activity of dredging vessels)	Vessel activity sequencing	Track and analyze operational behavior to link activity to emissions	Agent types (e.g., WID, TSHD) Sequence and timing of operations
Dependencies (Inter-dependencies and constraints)	System constraints	Identify operational preconditions, limits, and interlinked activities	Activity sequencing (pre-/post-processing) Tidal restrictions Vessel power limitations Interactions between vessels and site conditions

Table 4.2.: Using the perspectives to define requirements.

Perspective	Requirements	Data and attributes
Scales (Spatial patterns of maintenance dredging emissions)	Fundamental components	Activities timestamp
	Aggregation means	Activities sequence
Conditions (Influence of project and vessel properties on emissions)	Influencing factors	Water depth, vessel speed, sailing distance
	Coupling factors	Intermediate calculations
Behaviors (Understand the impact of vessel activities on emissions)	Agent identity	Vessel type, site name, vessel activity
	Activity sequence	Time stamps
Dependencies (Operational restrictions)	Initiations	Tidal period

represent the sailing path with uniform conditions. This scale-based characterization defines the maximum resolution (maximum zoomed-in level) of the modeling of time, location, and process flow, forming the foundation for reliable emission and duration estimates. The maximum zoomed-out level is achieved by aggregating values from the specified components. Note that for the example given here, the difference between the zoomed-in and the zoomed-out perspective is not very large, but it is easy to see how adding more detail in the analysis would affect this difference.

CONDITIONS

The factors influencing the estimation of emissions are classified into the characteristics of the project and the vessel, as well as the energy estimation modeling provided in Section 4.2.1. Vessel properties and project specifications are collected from the dredging contractors' in-house database, while tidal amplitude and dredging depth can be extracted from public websites associated with the port authorities. To have a realistic estimate of propulsion power, the resistance terms posed to the vessel hull and the dredging-related appendages are studied in detail, when the TSHD has more complicated dredging-related appendages with a visor, cutting teeth, and suction pipes. Therefore, the draghead-sediment interaction is quite influential on the propulsion power during dredging, while the jet beam-sediment interaction in the WID can be almost neglected. Meanwhile, the size of the dredging-related appendages, the number of nozzles, and nozzle diameters play an important role in the dredging phase of both vessels when dredging a sediment layer with the same properties (density, porosity, permeability).

The pump power is estimated based on a basic method proposed by Brown (2002), incorporating the flow rate and pump head used to overcome the pipeline resistance. These inputs directly influence energy use and operational timing and thus play a central role in quantifying the trade-offs between performance and emissions in port maintenance dredging. These inputs directly influence energy use and operational

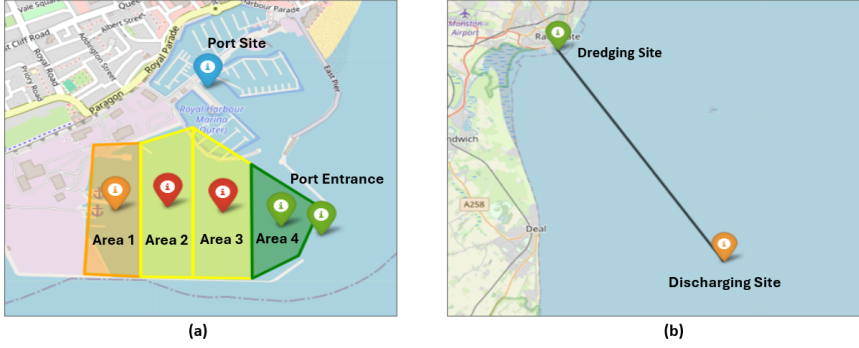


Figure 4.1.: Port site and dredging areas in the Port of Ramsgate (a) when using a WID; and (b) when using a TSHD (Source: OpenStreetMap).

4

timing and thus play a central role in quantifying the trade-offs between performance and emissions in port maintenance dredging. By incorporating local conditions to estimate required power, fuel consumption, and emissions, we can explicitly assess how site-specific environmental factors shape energy usage and emission levels. Coupled with the scales perspective, this enables us to identify where and when emissions occur and how these patterns are linked to underlying physical conditions.

BEHAVIORS

When it comes to the behavior perspective, the problem is formulated in a way that emissions can be traced based on the vessel type. Moreover, the simulation distinguishes between various vessel and site-specific parameters. Routing through the port system is predefined to cover four designated areas in the harbor site, providing a realistic operational context. OpenCLSim, built on the SimPy engine, supports both agent-based and discrete-event modeling. Agents, such as vessels, sites, or sediment traps, are defined with key attributes like capacity and operational thresholds. Activities of one agent (e.g., sailing, dredging, discharging) are modeled with defined durations and timestamps, allowing precise tracking of sequence and performance. This structure enables the simulation of real-world interactions and provides insight into how vessel behavior influences emissions and project efficiency (Sepehri *et al.*, 2024b).

This behavior modeling is particularly useful for trade-off analysis. For example, reducing sailing or dredging speed (a practice known as green steaming) can lower emissions but also increase project duration. The simulation enables stakeholders to explore such trade-offs dynamically, identifying operational scenarios that best align with their priorities, whether minimizing time or emissions. By linking operational behavior directly to energy consumption and emission outputs, this perspective provides a robust foundation for selecting appropriate dredging strategies under varying project constraints.

DEPENDENCIES

It is assumed that the operation of the WID vessel is constrained by tidal conditions, which is considered as a separate vessel-activity-timestamp, although the vessel doesn't do any dredging or sailing. A sinusoidal tide function is used to model this, allowing the vessel to operate only during outgoing tides. To accurately represent tidal behavior, the function incorporates tidal amplitude and phase shift, which adjust the timing and pattern of the sine wave. The tidal period, defined as the duration of a full tidal cycle, is set to 12.42 hours, corresponding to a semi-diurnal tide that occurs twice daily. When tidal conditions are unfavorable, the vessel remains stationary at the port site in the preparation phase. The water level h at any time t can be estimated as follows.

$$h(t) = \frac{A}{2} \times \sin\left(\frac{2\pi t}{T} - \phi\right) \quad (4.3)$$

where

- A is the tidal amplitude (the difference between high and low tide),

- T is the tidal period (assumed 12.42 hours for semi-diurnal tides),
- ϕ is the phase shift (aligning the tide cycle with real-world conditions).

The direction of the tide, whether incoming or outgoing, is determined by the rate of change in water level as follows.

$$\frac{dh(t)}{dt} = \frac{A\pi}{T} \times \cos\left(\frac{2\pi t}{T} - \phi\right) \quad (4.4)$$

A positive derivative indicates an incoming tide (rising water level), while a negative derivative indicates an outgoing tide (falling water level). Dredging operations with the WID are affected by tidal currents for both operational efficiency and environmental protection. Therefore, dredging is only permitted during outgoing tides to prevent sediment from spreading into harbors or sensitive ecosystems. Additionally, outgoing tides facilitate sediment transport away from the dredging area. To accommodate these tidal dependencies, the pre-processing function of OpenCLSim has been adapted to determine when dredging can commence and how long the vessel must wait for suitable conditions. During incoming tides, the vessel remains idle in the preparation phase, resuming operations only when the next outgoing tide begins (Pledger *et al.*, 2021). It is assumed that the TSHD operates without tidal restrictions. Tidal window information can be extracted from public websites associated with the port authorities.

4

4.3. RESULTS

To build the event table, different events are analyzed for two vessel types and the activities performed by each of them. The timestamp is shown based on the start time and end time of the activity, and the attributes of each activity are derived from the conditions, behavior, and dependencies perspectives presented in Section 4.2.2. Tidal restrictions for the WID are classified as a separate activity called “preparing,” which has its time stamp and attributes. The power consumed per power source, total power consumption, total energy consumption, and total emissions are included as attributes in the event table for each event.

Sediment mixture is mainly silt and clay material with a density of less than $1.3 \text{ tons}/\text{m}^3$ with an average grain size diameter of $175 \mu\text{m}$. Tidal amplitude is considered 2 hours, while the phase shift of -0.35 and tidal period of 12.42 hours are obtained from the observations. It is assumed that the WID vessel sails at a speed of and a maximum of 4 knots and dredges the area at a maximum speed of 1.5 knots. There is mobilization distance between HEE and LEE (average 450 meters) is considered a determining factor to estimate the productivity of the vessel in each area. Both vessels use two propellers for sailing and dredging, which is accounted for when estimating the propulsion power consumption. The TSHD vessel has a sailing speed of 10 knots, which is affected by the amount of loaded sediment inside the hopper bin.

The results obtained from the simulation of activities are used to fill the event table. The final attributes that are used for emission estimation are power and energy consumption. Table 4.3 summarizes these results in an event table constructed for a single dredging cycle of each TSHD and WID vessel. The power estimation per event is done based on the theoretical models, and the total duration of each event is estimated based on the production calculations. Total energy consumption per event is calculated by multiplying the power estimate value by the event duration. The estimation of CO_2 emissions for the entire dredging project is based on the assumption that both vessels operate on Marine Gas Oil (MGO) with 0.1% sulfur content.

Table 4.3.: Results of the event-based emission estimation model for activities in a single dredging cycle.

Event					Attributes							
Vessel ID	Activity name	Start time	End time	Location	Propulsion power [kW]	Jet pump power [kW]	Dredge pump power [kW]	Bow thruster power [kW]	Board net power [kW]	Total power [kW]	Total energy [kWh]	Total CO ₂ [ton]
WID 1	preparing	04:30	10:44	port site	–	–	–	–	20.88	20.88	130.36	0.09
WID 1	dredging trip	10:44	11:01	port to area 4	25.39	–	–	53.40	20.88	99.67	28.68	0.02
WID 1	dredging	11:01	16:57	area 4	154.59	766.30	–	53.40	20.88	995.18	5893.65	4.48
WID 1	port trip	16:57	17:14	area 4 to port	25.39	–	–	53.40	20.88	99.67	28.68	0.02
TSHD 1	sailing empty	04:30	05:18	discharge to dredge site	3475.90	–	–	44.00	182.00	3701.90	2965.17	2.54
TSHD 1	loading	05:18	05:34	dredging site	2153.62	919.52	1746.48	44.00	182.00	5045.63	1420.45	1.21
TSHD 1	sailing full	05:34	06:29	dredge to discharge site	2204.60	–	–	44.00	182.00	2430.60	2213.30	1.89
TSHD 1	unloading	06:29	06:30	discharge site	0.41	919.52	–	44.00	182.00	1145.94	17.18	0.01

In order to show the emission distribution among different events, two separate heat maps are presented in Figure 4.2, representing the intensity of emission estimates when dredging a certain area with a WID and a TSHD. In general, employing a WID contributes to considerably lower CO₂ emissions compared to the same case of using a TSHD. It is also shown that areas closer to the LEE have a less intense emission profile, as the energy needed to re-mobilize the sediments in these areas and relatively lower than in the more inner areas. Also, sailing events of a WID are not very energy-consuming and result in lower emission profiles. Higher emissions due to adopting a TSHD are because of two sailing events, while the vessel moves with higher velocities compared to the loading (trailing) and dumping events.

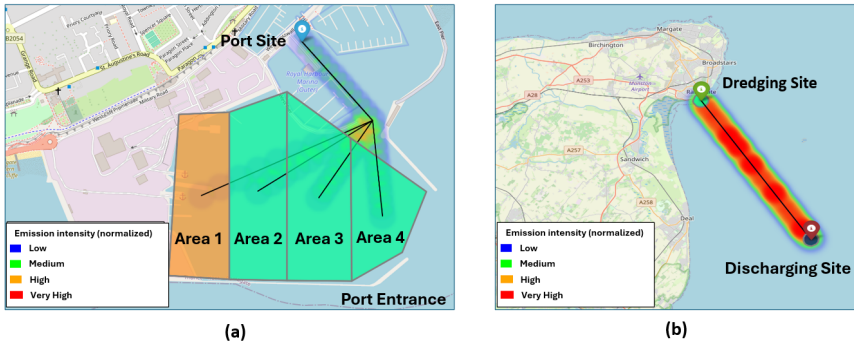


Figure 4.2.: Heatmap of CO₂ emissions when using (a) a WID and (b) a TSHD.

More detailed estimation of attributes per event is shown in Figures 4.3 and 4.4, in which the estimated values of power consumption, duration, energy usage, and emissions are presented for the whole project. To complete the dredging of the total sediment volume (135000 m³), the WID and TSHD vessels finish 8 and 30 dredging cycles, respectively. The WID vessel needs fewer cycles as it can work continuously within the dredging site, and only tidal conditions affect its workability, while the TSHD has a limited hopper volume (4500 m³) that needs to be filled once per cycle.

Estimation of events' attributes is validated through comparing these values to the values obtained from vessel logs and activity logs of the WID vessel dredged in the area in June 2024. Event durations obtained from activity logs are compared to the estimated duration values shown in Table 4.3 based on the simulations in OpenCLSim. Figure 4.5 represents a comparison between these values based on tidal windows, vessel speed, and production rate, showing an agreement between the duration of different events. Slight differences between estimated and logged values occurred due to vessel efficiencies and different sailing routes the vessel chose during the project.

A comparison between power estimation and vessel logs is used to validate the event table values. Figures 4.6, 4.7, and 4.8 summarize both estimated and logged values of power consumption for the propulsion system, jet pumps, and bow thrusters in the WID vessel. During the initial sailing phase, the vessel's speed increases to about 4 knots en route to the dredging site. While dredging, the speed reduces to between 0.5 and 1.5 knots. In the preparation phase, the vessel remains stationary, resulting in zero propulsion power consumption. Fluctuations during dredging are due to back-and-forth vessel movements within the dredging area. Jet pump power is measured during a specific dredging cycle between 04:00 and 12:00, encompassing sailing, dredging, and preparation phases. Jet pump power increases gradually at the start of dredging until reaching a steady operational level. The vessel is equipped with two jet pumps (starboard and port side), each approximately 400 kW, with a total installed jet pump power not exceeding 800 kW. The bow thruster power consumption varies significantly during sailing and dredging, while no power is used during preparation. These fluctuations are shown in the logged values, reflecting vessel maneuvering as it accesses different dredging locations. The simulation assumes a constant fraction of installed bow thruster power is applied across phases, but actual data reveals more dynamic and variable usage. The horizontal blue line shown in the figures represents the average estimated value of each power consumption.

According to the obtained model output and validations with real-world data, the WID vessel has fewer emissions than the TSHD but needs more time to dredge the same volume of sediment in the Port of Ramsgate. Despite the quicker operation by the TSHD, emissions are considerably higher due to the sailing phases, which have some room to optimize the sailing distance in a way that dredged sediment doesn't return to the port area,

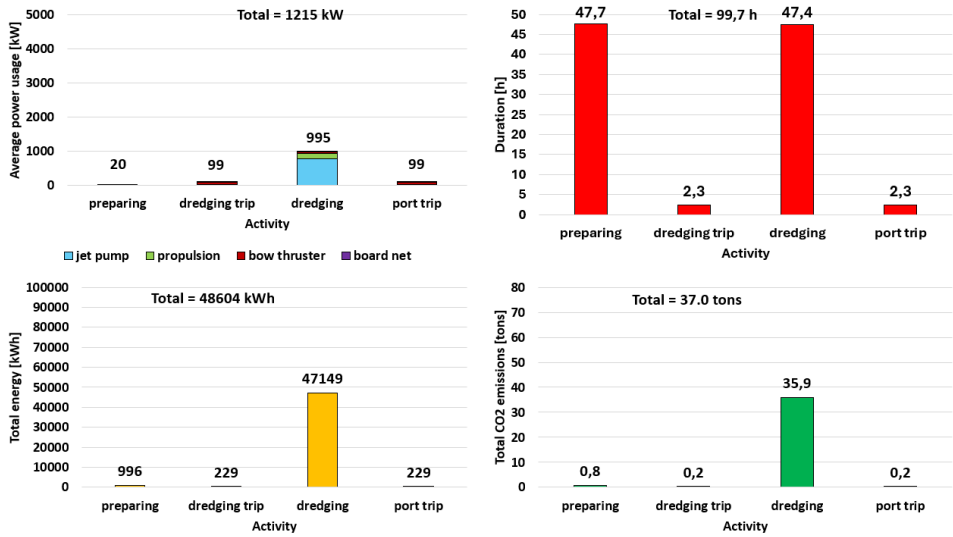


Figure 4.3.: Estimation of event-level attributes for the WID strategy, showing propulsion power, jet pump power, bow thruster power, total power demand, energy consumption, duration, and CO₂ emissions for all events.

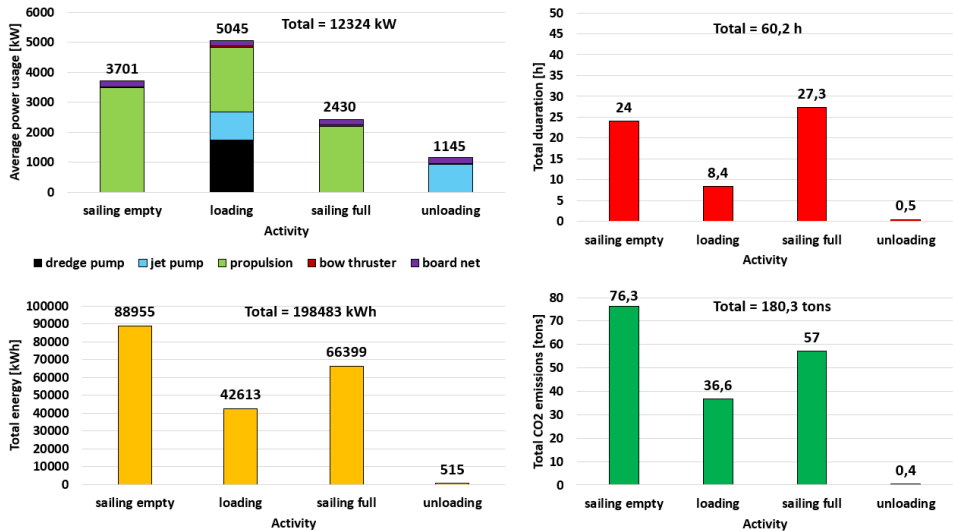


Figure 4.4.: Estimation of event-level attributes for the TSHD strategy, showing propulsion power, dredge pump power, bow thruster power, total power demand, energy consumption, duration, and CO₂ emissions for all events.

time restrictions are met, and emissions are minimized. In order to achieve this balance, local circumstances in a project play an important role. For instance, if maintenance dredging causes a bottleneck hindrance for port traffic, the faster strategy is preferred to avoid any disruptions; however, if the dredging is done according to the plan, using a WID with significantly less emissions would be a better option despite its slower dredging

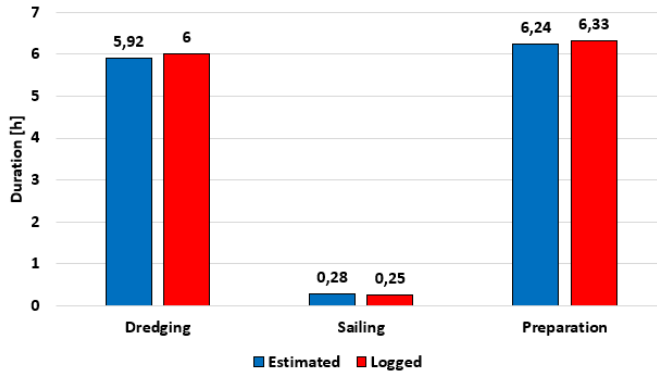


Figure 4.5.: Estimated versus logged activity durations for the WID.

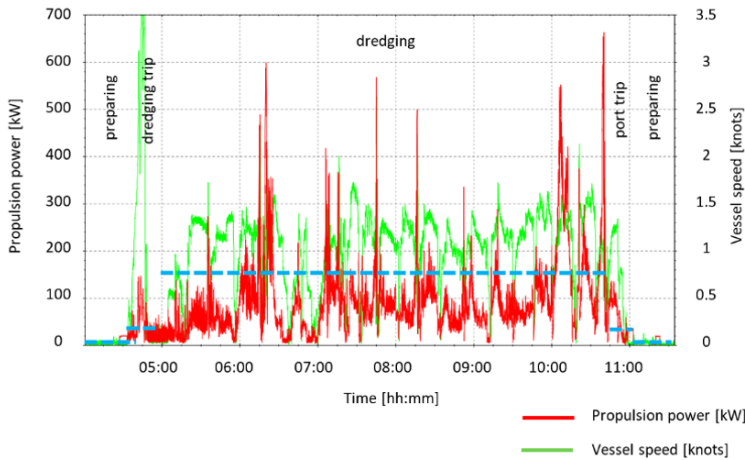


Figure 4.6.: Logged propulsion power (estimated values for preparing: 0, dredging and port trips: 25.39, and dredging: 154.59).

speed. The suggested approach in this study does not intend to decide on which equipment is better in general; rather, it analyzes both methods in detail so that, based on the obtained information, one can decide which method to select.

4.4. DISCUSSION

This study evaluates three maintenance dredging strategies at the Port of Ramsgate, emphasizing the use of a WID based on sediment characteristics, project parameters, and vessel properties. The proposed power and duration estimation model demonstrates strong agreement with actual vessel and activity logs, confirming its predictive accuracy. For WID operations, the pump working point was calculated considering head and pressure constants alongside total losses during dredging. Propulsion power estimates were derived following methodologies by Holtrop and Mennen (1982) and Miedema *et al.* (2007). Dredging durations accounted for production rates and tidal constraints, with the vessel assumed stationary during preparation phases. Incorporating tidal dynamics and distances from dredging sites to the port entrance further refined production rate estimates.

A key contribution is the quantification of trade-offs between time and CO₂ emissions across three dredging

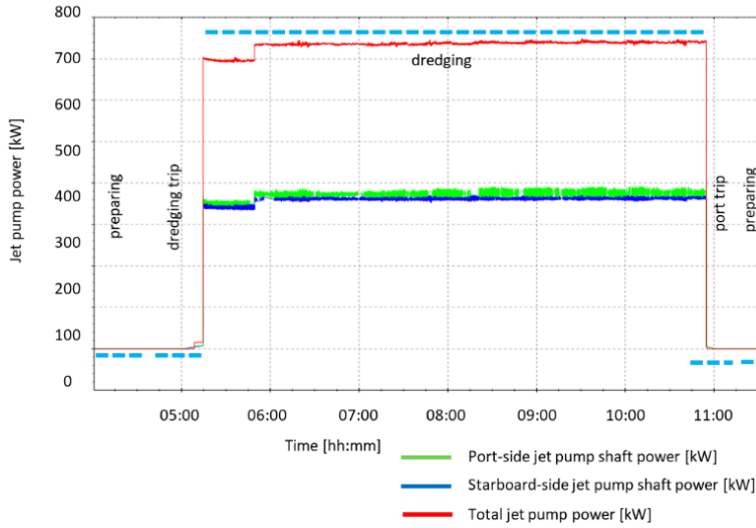


Figure 4.7.: Logged jet pump power (estimated values for preparing: 0, dredging and port trips: 0, and dredging: 766.30).

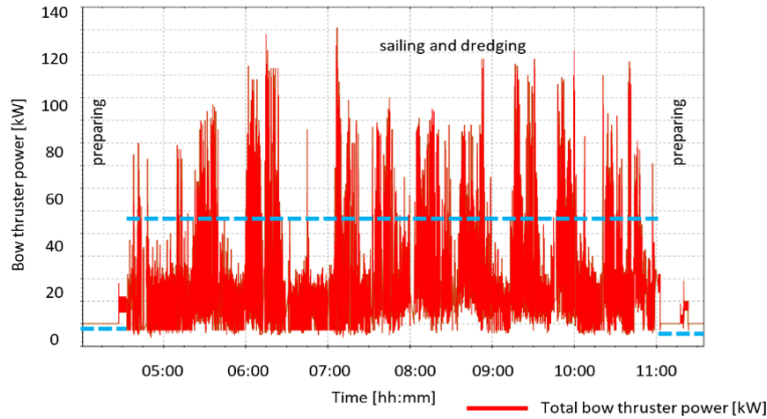


Figure 4.8.: Logged bow thruster power (estimated values for preparing: 0, dredging and port trips: 53.40, and dredging: 53.40).

strategies. TSHDs generally achieve higher production rates and are less constrained by tidal windows, enabling shorter project durations. However, TSHDs exhibit substantially higher energy consumption and associated emissions when using the same fuel type. To date, the literature has not adequately quantified this time-emissions trade-off, nor provided robust estimates of WID power consumption and operational windows. This research bridges these gaps by integrating scientific and empirical methods to estimate equipment production, power use, and carbon emissions for each strategy. These insights empower stakeholders, dredging contractors, port authorities, and terminal operators to better align project planning with environmental considerations and select optimal dredging approaches tailored to their port systems.

Despite its contributions, the study has limitations affecting model precision. Activity logs rely on short codes that omit detailed operational context. The model assumes uniform distances between points, disregarding vessel maneuvering and complex dredging trajectories. Additionally, it assumes continuous

operation of all energy-consuming systems during each activity phase, which may not reflect real-world variability, such as partial propulsion and bow thruster use depending on maneuvering and sediment conditions.

The study focuses on only two dredging vessel types (TSHDs and WIDs), excluding other relevant equipment like plows, backhoes, and grab dredgers, which could also be viable depending on availability and project needs. To advance maintenance dredging modeling, future research should consider

- **Refining Estimation Models:** Incorporate detailed parameters for vessel resistance, propulsion efficiency, and dredging component design (e.g., dragheads and jet pipes) to improve power and duration predictions.
- **Expanding Equipment Types:** Include a broader range of dredging machinery to offer a more comprehensive assessment of potential strategies, linked to equipment availability.
- **Improving Production Rate Accuracy:** Develop sediment models that capture sedimentation dynamics during projects and evaluate interactions between vessel components to better estimate peak power demands.
- **Integrating Environmental Regulations:** Factor in carbon policies and environmental constraints to aid contractors in selecting compliant fleets while balancing cost and emissions.

Ultimately, dredging fleet selection depends on multiple factors, including policy, equipment availability, and mobilization costs, typically decided during tender phases and negotiated with stakeholders.

4.5. CONCLUSION

This study contributes a novel, integrative framework for estimating emissions and evaluating alternative maintenance dredging strategies, grounded in both physics-based modeling and empirical validation. By incorporating vessel characteristics, sediment properties, and project-specific constraints, the proposed approach allows for realistic, situation-specific emission assessments. Applying this method to a case study at the Port of Ramsgate, the research demonstrated the predictive accuracy of power and duration estimates for both TSHD and WID operations and highlighted the trade-offs between project duration and emissions. The findings confirm that while TSHDs may offer shorter execution times due to higher production rates and reduced sensitivity to tidal conditions, they also generate significantly higher emissions.

In contrast, WIDs provide an environmentally favorable alternative under certain sediment and operational conditions, despite longer project durations. By quantifying these trade-offs, this study equips port authorities and contractors with data-driven tools to support strategic dredging decisions that balance operational efficiency and sustainability goals. Overall, this research addresses key gaps in the literature by moving beyond generalized emission estimates to offer a detailed, adaptable methodology that can be reused for a variety of port maintenance contexts. The framework supports more informed equipment selection and encourages environmentally responsible dredging practices, while future enhancements can further improve model precision and broaden applicability to additional dredging technologies and regulatory contexts.

5

CIRCULAR PORT MAINTENANCE

Systems are defined not only by their components, but also by their boundaries.

Donella H. Meadows

*This chapter addresses **Sub-question 4: How can the circularity aspect of sediment-reuse strategies be quantified and distinguished from traditional linear maintenance methods?** by developing quantitative indicators to assess the circularity of maintenance dredging strategies, with particular emphasis on sediment reuse. The methodology introduces Material Re-utilization Score (MRS) and Material Circularity Indicator (MCI) based on sediment re-usability and sediment retention, designed to distinguish circular sediment management from traditional linear reallocation practices. These indicators explicitly account for spatial and temporal system boundaries.*

A comparative case study of the Kleirijperij pilot project contrasts a conventional offshore sediment reallocation strategy with a circular reuse scenario involving dike reinforcement applications. Material flows, energy consumption, and emissions are structured using an event-based framework, allowing short-term dredging activities to be linked to long-term reuse outcomes. The results show a comparison between these two scenarios regarding cost, duration, energy consumption, CO₂ emissions, and circularity indicators.

The chapter concludes that circularity cannot be evaluated solely at the project scale of dredging operations. Instead, it requires explicit consideration of spatial and temporal boundaries. The proposed indicators provide a quantitative foundation for incorporating circular considerations into maintenance strategy selection, enabling material performance to be assessed alongside operational and environmental performance.

This chapter is based on an under review research paper as:

A. Sepehri, & A. Kirichek, & M. van den Heuvel, & M. van Koningsveld, M.(2026). "From linear to circular port maintenance dredging: A case study of beneficial reuse of sediments". In: *Journal of Soils and Sediments*

5.1. INTRODUCTION

Maintenance dredging is indispensable for ensuring the navigability and operational continuity of ports and waterways. However, it generates large quantities of dredged sediment, which have traditionally been treated as waste and often reallocated offshore (Carreira *et al.*, 2025). The traditional approach to maintenance dredging not only involves considerable logistical and environmental costs but also represents a missed opportunity to recover materials and close resource loops. In recent years, growing attention to sustainability, resource scarcity, and the European circular economy agenda has created momentum to rethink dredged sediments as valuable resources for beneficial reuse and ecosystem restoration (Van Koningsveld *et al.*, 2023; Laboyrie *et al.*, 2018).

Despite this growing awareness, the concept of circularity in maintenance dredging remains poorly defined and methodologically underdeveloped. While existing dredging studies are well advanced in identifying strategies for achieving the lowest operational cost, other value dimensions, such as material reuse, resource recovery, and broader environmental benefits, are still insufficiently addressed. Establishing a clearer conceptual and analytical foundation for circularity is therefore essential, as it would enable the inclusion of currently overlooked forms of value in the evaluation and comparison of different dredging strategies (Sepehri *et al.*, 2024a).

This study aims to address this methodological gap by developing an approach to quantify circularity in maintenance dredging. The approach is designed to capture how materials, energy, and processes contribute to circular outcomes within a port maintenance context. To operationalize it, the study adapts concepts from both the general circular economy literature and the construction sector, where circularity measurement and material flow assessment are more mature. The approach is demonstrated through a case study at the Port of Delfzijl (the Netherlands), comparing two contrasting maintenance dredging scenarios:

1. A **linear approach**, that is generally represented by conventional offshore reallocation using a Trailing Suction Hopper Dredger (TSHD) and follows the traditional “extract–use–reallocate” model.
2. A **circular approach**, that embraces the beneficial reuse of dredged sediments for dike reinforcement, extending the material life cycle, and promoting resource recovery.

Through this comparison, the study explores how circularity can be described in quantifiable terms and how it interacts with operational parameters such as energy use, emissions, and time. The general Circular Economy (CE) literature provides a conceptual foundation for understanding and evaluating circularity. CE frameworks emphasize preserving material value, closing resource loops, and decoupling economic activity from resource consumption. Key mechanisms include reduction, reuse, recycling, and recovery, often referred to as the “4R” strategies, which form the backbone of circular design and resource management principles (Korhonen *et al.*, 2018; Mulder *et al.*, 2007). While more recent frameworks have expanded these principles into broader sets, such as the “9R” or “10R” strategies (Ramírez-Escamilla *et al.*, 2024), this study adopts the 4R framework for clarity and consistency with established literature in the dredging and resource management domains.

Quantifying circularity has been a major research focus across industries, leading to the development of metrics such as the MCI by the Ellen MacArthur Foundation and the Circularity Gap Metric, which assesses the proportion of materials retained in closed loops versus virgin input (MacArthur, 2015). These tools provide a means to measure progress toward circularity, yet they have primarily been applied to manufacturing and product systems rather than large-scale industrial processes such as dredging.

The broader CE literature also highlights the importance of system boundaries and value chain integration when assessing circularity. Circularity cannot be evaluated solely at the product or process level; it requires understanding interlinked flows of materials, energy, and value within and across systems (Kristensen and Mosgaard, 2020; Moraga *et al.*, 2019). These conceptual lessons are essential for translating CE thinking into the context of port maintenance, where multiple stakeholders such as port authorities, contractors, and environmental agencies interact within a dynamic operational network (Sepehri *et al.*, 2023; Niero and Kalbar, 2019).

The construction and infrastructure sectors have made significant progress in operationalizing circularity concepts, offering valuable analogies for maintenance dredging. Here, circularity is addressed through material reuse, deconstruction, design for adaptability, and life-cycle-based performance assessment. Several methodologies have emerged to evaluate circularity in construction materials and processes, such as Material Flow Analysis, Life Cycle Assessment, and Circularity Indicators that quantify retained material value or recovery potential (De Pascale *et al.*, 2021; de Souza *et al.*, 2024; Munoz *et al.*, 2024). The reuse of excavated soils, recycled aggregates, and demolition waste in civil engineering projects mirrors the reuse potential of

dredged sediments. These frameworks demonstrate how circularity assessment can move beyond qualitative descriptions toward measurable indicators that inform decision-making (Crocetti *et al.*, 2022; Ferrans *et al.*, 2022).

Moreover, the construction literature underscores that circularity involves trade-offs; for example, between material recovery and energy consumption, or between project duration and environmental performance (Almokdad and Zentar, 2023; Maletić *et al.*, 2019; Spadaro and Rosenthal, 2020). Such insights are particularly relevant to maintenance dredging, where operational choices (e.g., sailing distance, pumping energy, or sediment quality) directly affect both circular and sustainability outcomes (Sepehri *et al.*, 2024a; Dorleón *et al.*, 2025; Ulibarri *et al.*, 2020). By adapting lessons from these sectors, this study develops a dredging-specific approach that integrates material flow reasoning with circularity metrics. This enables both qualitative interpretation and quantitative comparison of alternative dredging scenarios.

Building on these conceptual foundations, the remainder of this paper presents the development and application of a circularity assessment framework for maintenance dredging, demonstrated through a discrete-event simulation of two dredging scenarios at the Port of Delfzijl. The framework provides a structured way to describe how materials circulate within the dredging process and how circular strategies influence energy use, emissions, and operational efficiency. Section 5.2 elaborates on the research methodology used to quantify the circularity of maintenance dredging projects and simulate different scenarios. Section 5.3 analyzes the results obtained from real-world data when simulating two separate scenarios and the modified circularity indicators. Section 5.4 discusses the findings in more detail, addresses theoretical and managerial implications, and proposes future research directions. Finally, Section 5.5 concludes the findings of this chapter.

5.2. METHODS

5.2.1. CONCEPTUAL MODELING OF CIRCULARITY IN MAINTENANCE DREDGING

To accurately quantify the contribution of a maintenance dredging project to circularity, it is necessary to systematically and measurably compare traditional linear and circular dredging approaches. Traditional maintenance dredging typically involves excavation and offshore reallocation or reallocation, whereas circular dredging seeks to retain and reuse sediments for beneficial purposes, such as reinforcing dikes. However, comparing these approaches is challenging because circular strategies introduce additional processes, material transformations, and temporal considerations. For example, reused dredged fine-grained sediment often requires time to mature into reusable clay, meaning that material availability is not immediate. Furthermore, differences in operational sequences, equipment usage, and process efficiency can create trade-offs between cost, emissions, and circularity outcomes. Capturing these trade-offs requires a framework that links operational performance to material retention and resource efficiency. To provide a holistic assessment, the framework considers three interrelated dimensions: operational performance, which evaluates project duration and costs; environmental performance, which accounts for energy consumption and emissions; and material performance, assessed through indicators of material retention and circularity.

OPERATIONAL PERFORMANCE

The total duration of a circular maintenance dredging project is determined by aggregating the time required for preparation, dredging cycles, and decommissioning processes to render the sediment reusable. Preparation and decommissioning durations depend on project planning and material properties, whereas dredging cycles are dictated by the chosen operational strategy and the specific activities performed, including loading, sailing, and discharging.

The total duration of a circular maintenance dredging project T_{total} is determined by aggregating the time required for establishing the maintenance dredging operations $T_{establish}$, dredging cycles T_{cycle} , and decommissioning processes $T_{decommissioning}$, which include the activities to render the sediment reusable and the removal of supporting infrastructure (See Equation 5.1). Preparation and decommissioning durations depend on project planning and material properties, whereas dredging cycles are dictated by the chosen operational strategy and the specific activities performed, including loading, sailing, and discharging.

Operational and environmental factors influence the duration of each activity. Sailing time depends on the distance between dredging and reallocation sites, vessel speed, and loading conditions. Dredging time is a function of the total sediment volume and the vessel's production rate, which reflects the efficiency of sediment excavation and is estimated based on sediment properties and dredging equipment configuration. For a TSHD, excavation production denotes the volume of material successfully loosened, collected, and transported from the seabed into the hopper. Key factors affecting production rate include sediment

properties, draghead efficiency, and suction pipe performance, which can be modeled by dividing the loading process into cutting, jetting, and erosion stages. Additionally, the filling cut-off criterion, which stops loading when the hopper bin is full, plays an important role, as it determines the effective hopper utilization and overall cycle efficiency. Finally, discharging duration depends on the method employed. In this study, the bottom-door method is adopted, which is primarily governed by sediment fluidization in the hopper and the vessel's storage capacity, while sailing times account for both loaded and unloaded conditions.

$$T_{total} = T_{establish} + \sum_{n=1}^{tot-nr-cycles} T_{cycle} + T_{decommissioning} \quad (5.1)$$

The estimation of total costs of a circular maintenance dredging project C_{cycle} largely follows a similar structure: (a) the preparation cost that includes the establishment and preparation of supporting infrastructure, (b) the cost of the accumulated dredging cycles, and (c) the cost associated with the activities to render the sediment reusable and the removal of supporting infrastructure (See Equation 5.2). These costs for preparation and establishing the infrastructure $C_{establish}$ include expenditures related to site preparation, construction of storage or treatment facilities, and supporting utilities. The cycle costs, on the other hand, the cycle costs C_{cycle} cover the day-to-day expenses incurred during the implementation phase, primarily consisting of equipment hire rates, fuel consumption, labor, and maintenance. Decommissioning costs $C_{decommissioning}$ covers the expenses for sediment processing before making it ready for reusing purposes and removal of the processed sediment to be transported to dikes. Together, all cost components provide a comprehensive understanding of the total financial requirements of the project, serving as a basis for evaluating its economic feasibility and potential scalability.

$$C_{total} = C_{establish} + \sum_{n=1}^{tot-nr-cycles} C_{cycle} + C_{decommissioning} \quad (5.2)$$

The detailed analysis of operational performance provides the foundation for assessing the project's environmental impact. Since each operational phase determines the vessel's activity duration and corresponding power requirements, these results directly inform the estimation of energy consumption and emissions. Consequently, the environmental performance analysis builds upon the operational framework by translating power demand and time-related parameters into quantifiable energy use and CO₂ output.

ENVIRONMENTAL PERFORMANCE

To assess the environmental performance of different dredging scenarios, total energy consumption and CO₂ emissions are considered the primary environmental indicators in this study. Other relevant indicators, such as turbidity and underwater sound, can also influence environmental impact assessments. A quantifiable method for estimating turbidity in dredging operations has been proposed by Becker *et al.* (2015), which can be integrated into similar assessment frameworks, while standardized methods for quantifying underwater sound impacts remain less established (Van Geel *et al.*, 2022). The detailed breakdown of operational performance, covering activity durations, location, vessel configurations, and equipment use, provides the necessary input parameters for this analysis.

Quantifying these operational characteristics makes it possible to estimate the total power consumption of the vessels and derive energy use based on the active operational duration of each component. Energy consumption per activity E_{act} is calculated as the integral of the power demand per activity P_{act} over the active operating duration, with the start time t_0 and the end time of the activity t_1 (See Equation 5.3). Total energy consumption E_T is calculated by aggregating the energy consumed per activity for all the dredging cycles (See Equation 5.4). For sailing operations, energy consumption can be derived using energy-based resistance models, where the total resistance and the corresponding required propulsion power are estimated to determine the energy per activity. The formulations by Holtrop and Mennen (1982), Lamers (2022), and Prins (2024) provide a suitable foundation for this approach. For loading and unloading operations, methods developed by Miedema *et al.* (2007), Janssen (2023), and Prins (2024) can be applied, where power and energy use are estimated based on factors such as engine and pump requirements, sailing speed, cut depth, material flow rate, and production cut-off criteria.

$$E_{act} = \int_{t_0}^{t_1} P_{act}(t) dt \quad (5.3)$$

$$E_T = \sum_{n=1}^{tot-nr-cycles} \int_{0,t_0}^{1,t_1} P_{act,i}(t) dt \quad (5.4)$$

Emissions EM_T are then estimated by Equation 4.1 based on the specific fuel consumption SFC and emission factors EF for the fuel type used, while accounting for engine load-related inefficiencies. Mitigating measures such as exhaust gas filters, scrubbers, or the use of alternative fuels are not considered in the present analysis, although they could be incorporated into the framework to evaluate potential emission reduction strategies in future applications.

To obtain an accurate estimate of power consumption, it is essential to understand both the power demand of each onboard component and the duration for which each component operates during a complete dredging cycle (Van der Bilt, 2019; Janssen, 2023; Lamers, 2022; Prins, 2024). A TSHD is equipped with several key systems, including the propulsion system, dredge pumps, jet pumps, bow thruster, and onboard electrical network. Depending on the four distinct operational phases of the dredging cycle, these components can be (in)active as summarized in Table A.1. Dredge pumps, located outside the vessel's hull between the draghead and suction pipe, are primarily responsible for generating suction pressure to lift the sediment-water mixture. Jet pumps, on the other hand, use pressurized water to fluidize the seabed material, facilitating sediment uptake and discharge (Brown, 2002). Bow thrusters act as transversal propulsion devices that enhance vessel maneuverability and keep the vessel in position during discharging, while the onboard electrical (board net) power distribution system ensures a continuous and reliable power supply to all auxiliary systems and equipment.

In this chapter, propulsion power is estimated based on vessel–fluid–sediment interactions, accounting for sediment properties, dredging appendage characteristics, and project-specific parameters. Pump power requirements for each operational phase are determined by identifying the pump working point, where the pump-generated head equals the total hydraulic resistance of the pipeline system. The duration of pumping is further governed by the filling cut-off criterion, which defines when the hopper is considered sufficiently filled, and the loading phase is terminated. The power demands of the bow thruster and the electrical network are assumed to remain constant throughout the dredging cycle.

MATERIAL PERFORMANCE

A key aspect of circularity in maintenance dredging is material retention and utility, encompassing both the proportion of dredged material ultimately available for reuse and the losses occurring during dredging, transport, and pre-treatment. These losses reduce the project's overall contribution to circular practices and should therefore be explicitly accounted for. Timing is another critical aspect, while the duration of dredging operations may differ from the time required for sediments to become suitable for reuse, influencing the realized circularity and project scheduling.

To quantify the material performance dimension, two complementary indicators are employed.

1. **MRS:** Measures the proportion of dredged material that is ultimately reusable, considering both Intrinsic Recyclability (IR), the percentage of material that can be reused at least once, and Recycled Content (RC), the fraction of reused material within the system (McDonough and Braungart, 2008).

$$MRS = \frac{[IR \times 2 + RC \times 1]}{3} \quad (5.5)$$

2. **MCI:** Evaluates how effectively dredged sediments follow a circular flow, integrating linear material losses and sediment utility (MacArthur, 2015; Niero and Kalbar, 2019).

Sediment utility X refers to how extensively the sediment can be reused for beneficial purposes. This function comprises two components: (a) the length component L/L_{av} refers to any changes in the waste stream in a given time for materials that have a different lifetime than the average lifetime; (b) the intensity of use component U/U_{av} reflects the extent to which the materials are used when considering the total cubic meters during material reuse and an industry-average material of a similar type.

$$X = \left(\frac{L}{L_{av}}\right) \times \left(\frac{U}{U_{av}}\right) \quad (5.6)$$

The linear flow index LFI measures the proportion of sediments flowing linearly, sourced from dredged sediments, and ending up as unrecoverable waste. The LFI is calculated by a division of linear material

flow by total material and takes a value between 0 and 1, where 1 is a completely linear flow and 0 is a completely restorative flow.

$$LFI = \frac{M_{reallocation}}{M_{reallocation} + M_{loss.reuse}} \quad (5.7)$$

Therefore, MCI is calculated based on the extent to which the dredged material follows a circular flow in the system and a sediment utility function $F(X)$. The $F(X)$ value can be negative for products with mainly linear flows $LFI \approx 1$ and a utility index worse than an average product $X < 1$. To avoid this, the MCI is defined as

$$MCI_p = 1 - LFI \times F(X), \quad F(X) = \frac{0.9}{X}, \quad MCI = (0, MCI_p) \quad (5.8)$$

In this context, Tons Dry Solid (TDS) is used as the reference parameter to represent the actual mass of solid material within the dredged sediments. This choice ensures that only the recoverable and reusable fraction of the material is considered, excluding the variable water content that does not contribute to material circularity. Using TDS rather than in situ volume or total wet mass provides a more consistent and comparable measure of material retention, as water loss during handling or processing does not equate to material loss in a circularity assessment. In addition, it is essential to define the spatial and temporal boundaries of the circular system, specifying where and for how long sediment is considered part of the circular loop. Although sediment always remains on the planet, only the fraction that stays within the defined system boundaries is regarded as circular, emphasizing the importance of explicitly delineating these limits in the assessment.

EVENT TABLE AND CASE DESCRIPTION

To address the multi-dimensional nature of operational, environmental, and material performance, this study employs a discrete-event simulation framework based on the open source Python library OpenCLSim (de Boer *et al.*, 2023a; Van Koningsveld *et al.*, 2019), where additional code developed for production and energy consumption estimation is stored in a private GitHub repository and can be shared upon request. OpenCLSim enables detailed modeling of dredging activities, including vessel movements, operational sequences, and resource consumption such as energy and power. Through the discrete-event approach, the framework explicitly captures the dynamic interactions and dependencies between operational, environmental, and material processes. By integrating activity-level simulation, physics-based modeling, and circularity indicators, it enables a systematic evaluation of trade-offs between linear and circular maintenance dredging, linking operational efficiency, material retention, and environmental impact within a single, comparable structure for evidence-based decision-making.

A systematic quantification approach is required to examine the problem from multiple perspectives without repetitive procedures and to enable dynamic transitions between different levels of detail when analyzing factors such as cost, time, energy, and circularity. To achieve this, we adopted the “event table” concept proposed by Van der Werff *et al.* (2025) to structure the simulation results linked to unique vessel activities and operational scenarios. The event table is structured around the definition of scenarios, events, and attributes, allowing for a detailed comparison of work methods across scenarios. It is organized according to four key perspectives: scale (temporal and spatial specifications), conditions (environmental and vessel-specific factors), behavior (sequence of activities), and dependencies (activity prerequisites). Table 5.1 summarizes these perspectives for the case of circular maintenance dredging.

To better understand the scale of maintenance dredging, this analysis provides a detailed overview of the project, emphasizing both the spatial and temporal dimensions of dredging activities. The scale perspective defines the locations and time frames in which each activity occurs. The Port of Delfzijl (Figure 5.1a) is selected as the case study area. A second scenario considers the discharge of dredged sediment into fifteen separate clay ripening compartments situated within the navigation channel (Figure 5.1b). This project, known as “Kleirijperij”, promotes circularity by enabling the dredged sediment to ripen and subsequently be reused as clay material for dike reinforcement in the Netherlands.

Two scenarios are established to assess the influence of circularity on key performance indicators. The first scenario represents conventional maintenance dredging in the Port of Delfzijl, involving repeated sailing between the port basin, a turning point, and offshore reallocation sites. The second scenario represents a circular dredging approach consisting of two distinct dredging phases, one conducted between 7 and 12 April 2018, during which approximately 105,000 m^3 of sediment was pumped into ripening compartments, and

Table 5.1.: Perspectives for circular maintenance dredging.

Perspective	Focus	Requirements	Data and attributes
Scales	Time and space definition	- Define system boundaries and spatial resolution - Determine dredging duration and operational time steps - Map vessel movement patterns	- Coordinates of sites, routes, and system boundaries - Start/end time per activity - Activity sequence identifiers
Conditions	Environmental and operational drivers	- Characterize sediment, hydrodynamics, vessel specifications - Incorporate operational limits	- Sediment density, grain size, water depth - Vessel speed, sailing distance, pump power - Intermediate performance calculations
Behaviors	Sequence and scheduling of activities	- Identify operational agents (vessels, sites) - Define activity order and duration dependencies	- Vessel and site type - Activity type (e.g., dredging, sailing, discharging) - Duration and timestamp records
Dependencies	Activity interrelations and prerequisites	- Specify pre- and post-processing requirements - Define conditional triggers between sequential activities	–

another between 11 and 13 July 2018, during which approximately 89,000 m^3 was pumped into ripening compartments. In this case, the dredged material was discharged into clay ripening compartments using an onboard discharge pump.

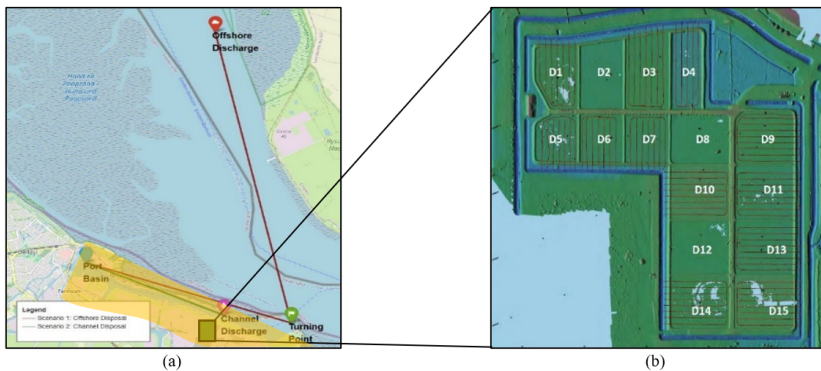


Figure 5.1.: Schematic picture of the Kleirijperij project on (a) dredging, discharging, and reusing activities; and (b) ripening compartments (Koster *et al.*, 2023) (Source: OpenStreetMap).

The circular system boundary, illustrated as the orange-shaded area in Figure 5.1a, defines the spatial system within which sediment reuse is considered to contribute to circular port maintenance. It encompasses the port basin, nearshore zones, and designated onshore placement areas where dredged material can be retained and repurposed. This boundary must be explicitly defined in advance, by the client, contractor, or analyst, since quantifying circularity is only possible once the spatial limits of the system are established. Without such a definition, the assessment would be conceptually open-ended, as sediment ultimately remains on the planet and could, at geological timescales, always be considered part of a larger circular system. In addition to spatial limits, it is equally important to define temporal boundaries, indicating the period within which reuse is considered relevant to circularity. For instance, if clay ripening occurs within the spatial boundary but requires several decades (e.g., 50 years) before reusing, it would likely fall outside the practical temporal boundary of the circular system. Consequently, the first scenario, where sediment is discharged offshore, falls outside this

boundary and does not qualify as circular.

A multi-criteria trade-off analysis is employed to compare both scenarios across, including cost, duration, energy consumption, and emissions. Additionally, a circularity index is calculated for the second scenario to assess its contribution to circular dredging practices. The findings indicate that the spatial configuration of locations and the vessel's capacity substantially influence the total duration, and consequently, overall energy use and emission levels. The indicators in this analysis are determined by the combined effects of vessel characteristics, sediment properties, and project configuration. To simplify the assessment, the average power requirements of the TSHD used in the project are derived from open-source data. The project duration for each scenario is then estimated through simulations of vessel movements between the operational locations shown in Figure 5.1a.

5.3. RESULTS

To construct the event table, both scenarios are analyzed by defining their vessel activities and corresponding start and end times, derived from the simulated duration of each operation. Event attributes are obtained from physics-based models combined with simulation outputs. As the sediment mainly consists of silt and clay, and both scenarios involve a TSHD with a hopper capacity of 2470 m^3 , the event table summarizes the operational, environmental, and material performance of a single dredging cycle. Each event includes activity-specific attributes such as duration, cost, power, energy use, CO_2 emissions, and circularity indicators (See Table 5.2).

Vessel power consumption is estimated from publicly available vessel data and multiplied by activity duration to determine energy use. CO_2 emissions are then calculated using energy consumption, fuel use, and emission factors, assuming marine gas oil (MGO, 0.1% sulfur) as the fuel. Figures 3 and 4 compare both scenarios in terms of total duration, power, energy use, and CO_2 emissions. Scenario 1 shows a higher total power demand and longer duration due to the extended sailing distance to the offshore reallocation site, which also results in a greater number of sailing hours per trip. In contrast, Scenario 2 benefits from a shorter sailing route, leading to reduced propulsion power, energy use, and emissions per trip. Additionally, Scenario 2 requires higher energy input during discharge, as the material is pumped into clay ripening compartments through a booster-supported pipeline system.

Table 5.2.: Event table from the vessel perspective, comparing operational, environmental, and material performance.

Scenario	Event				Attributes							
	Event ID	Event name	Start time	End time	Operational performance			Environmental performance			Material performance	
					Spatial location	Duration [h]	Cycle cost [€]	Total power [kW]	Total energy [kWh]	CO ₂ [tons]	End MRS	End MCI
Scenario 1 (offshore reallocation)	Vessel 1	sailing empty to the turning point 1	7 Apr 2018 00:00	7 Apr 2018 00:25	discharging site to turning point	0.42	376.91	2129	899.61	0.77	0	0
		sailing empty to the port basin 1	7 Apr 2018 00:25	7 Apr 2018 00:28	turning point to the port basin	0.06	53.02	2129	126.55	0.10	0	0
		loading 1	7 Apr 2018 00:28	7 Apr 2018 01:43	port basin	1.23	1101.62	3479	4296.56	3.68	0	0
		sailing full to the turning point 1	7 Apr 2018 01:43	7 Apr 2018 01:47	port basin to turning point	0.07	64.21	2129	153.27	0.13	0	0
		sailing full to the discharging site 1	7 Apr 2018 01:47	7 Apr 2018 02:18	turning point to discharging site	0.51	456.48	2129	1089.53	0.93	0	0
		discharging offshore 1	7 Apr 2018 02:18	7 Apr 2018 02:24	discharging site	0.10	89.20	409	40.90	0.03	0	0
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	Scenario 2 (sediment reuse)	Vessel 1	sailing empty 1	7 Apr 2018 00:00	7 Apr 2018 00:02	storage compartments to the port basin	0.04	41.71	2129	99.55	0.09	1
loading 1			7 Apr 2018 00:02	7 Apr 2018 01:16	port basin	1.23	1101.62	3479	4296.56	3.97	0.99	0.65
sailing full 1			7 Apr 2018 01:16	7 Apr 2018 01:20	port basin to storage compartments	0.05	50.51	2129	120.57	0.11	0.99	0.66
discharging 1			7 Apr 2018 01:20	7 Apr 2018 01:53	storage compartments	0.54	489.60	1199	658.11	0.56	0.99	0.66
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Figures 5.2 and 5.3 compare both scenarios in terms of total duration, power, energy use, and CO₂ emissions. Scenario 1 shows a higher total power demand and longer duration due to the longer sailing distance to the offshore reallocation site, whereas Scenario 2 benefits from a shorter sailing route, leading to lower propulsion power, energy use, and emissions. However, Scenario 2 requires higher energy during discharge because the material is pumped into clay ripening compartments via a booster-supported pipeline system.

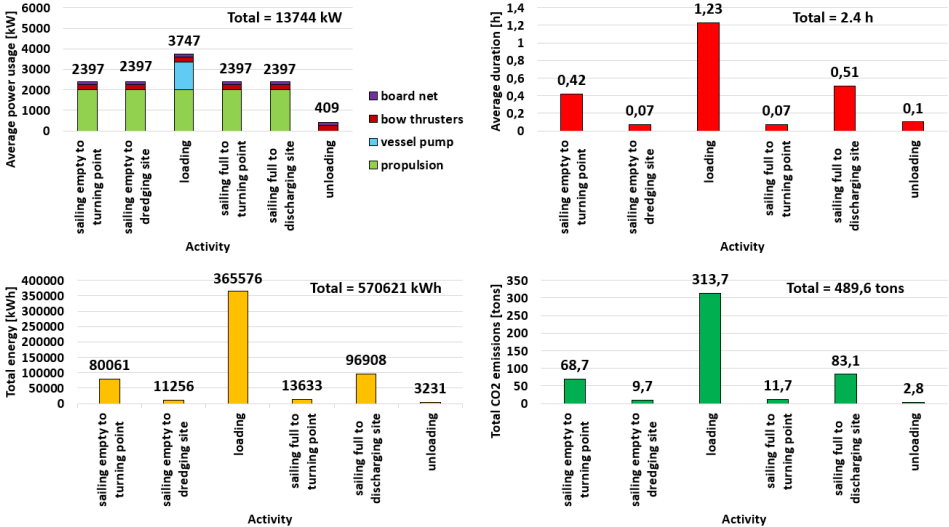


Figure 5.2.: Operational and environmental performance trade-offs for Scenario 1 (offshore reallocation).

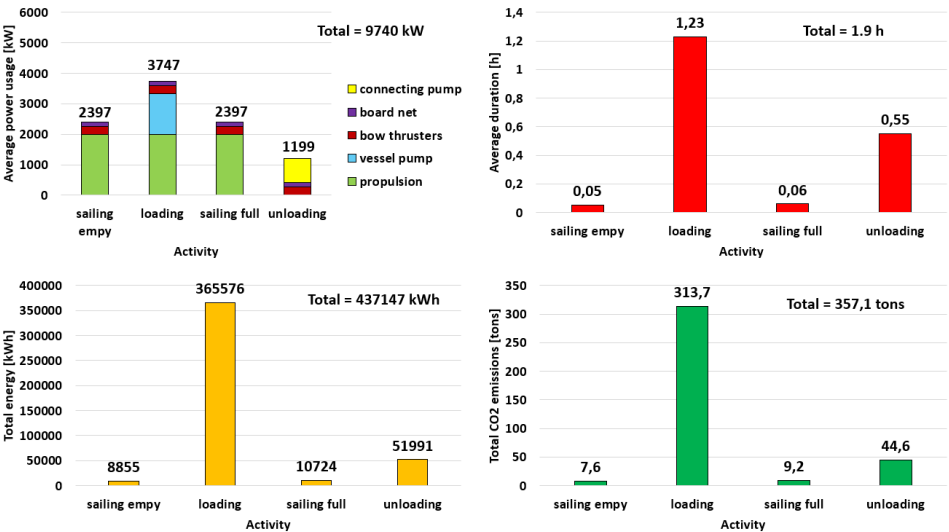


Figure 5.3.: Operational and environmental performance trade-offs for Scenario 2 (sediment reuse).

The operational costs of the TSHD are derived from publicly available charter rates for vessels of comparable size and capacity, while establishment costs are obtained from publicly accessible project reports (Koster

et al., 2023). The overall project timeline is presented in Figure 5.4, illustrating distinct phases including compartment establishment, dredging, ripening, and clay transportation. This analysis primarily focuses on comparing the operational performance of the project, focusing on duration of activities, and material performance, focusing on how material reuse and retention are analyzed using circularity indicators.

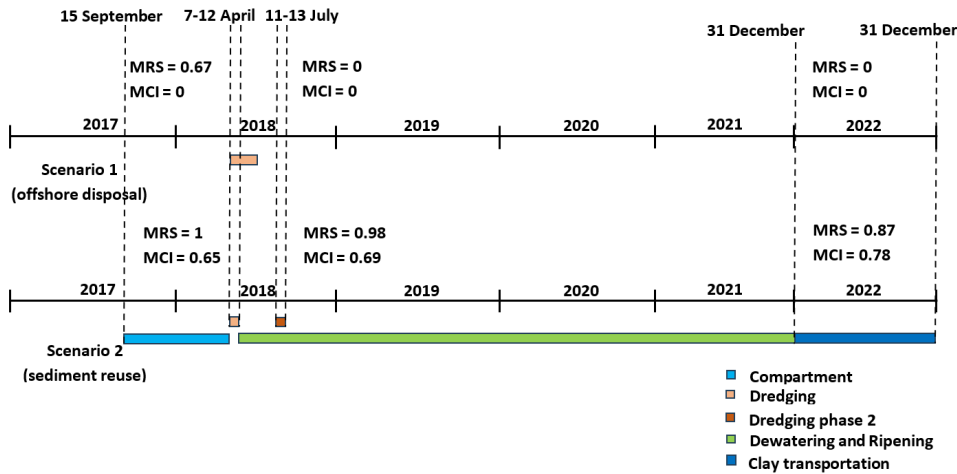


Figure 5.4.: Operational and material performance comparison for both scenarios.

Both the MRS and MCI vary throughout the project, as they are directly influenced by the re-usability of dredged materials. Assuming that all dredged sediments are initially recyclable, the MRS is set to 1 (or 100%) at the beginning of the project, reflecting the intrinsic recyclability of the TDS. Over time, however, the MRS gradually decreases due to sediment degradation, leading to a reduction in the fraction of reusable material by the end of the project. Conversely, the MCI increases over time, as it reflects the actual material recovery and reuse, which improve as the project progresses toward sediment ripening and reuse. However, only the portion of sediment that remains within the circular system boundary contributes to the MCI. Sediment that falls outside this boundary, such as material that is not reused or recovered, does not contribute to circularity. Therefore, Scenario 1 shows an MCI value of 0, as all sediment in that case falls outside the circular system boundary. The final values of the MRS and MCI are thus interpreted as the project's overall contribution to circularity.

The actual TDS obtained in the project differed from expected values due to dredging inefficiencies and material losses before full sediment transfer to the compartments. Over time, the TDS content in each compartment declined, mainly influenced by the organic matter degradation of the sediments. The two filling phases, conducted in April and July 2018, and the final extraction in September 2020, resulted in an accumulated TDS of about 42,375 tons, lower than the initially loaded mass, indicating material degradation. A detailed sediment state-related event table, summarizing these filling and extraction phases alongside key compositional changes, should be included to clarify the temporal evolution of sediment conditions. Based on these solid material losses, circularity indices were calculated assuming the ripened clay met industry-average quality standards ($F(X) = 0.9$) suitable for dike reinforcement. The analysis showed that MRS and MCI indicators applied only to Scenario 2, as Scenario 1 involved no material reuse, thereby highlighting the circular contribution of the clay ripening process. Table 5.3 shows an event table for sediment state changes during each scenario.

Table 5.3.: Event table from the sediment perspective, comparing operational and material performance.

Scenario	Event				Attributes								
	Event ID	Event name	Start time	End time	Operational performance				Material performance				
					Spatial location	Duration [h]	IR	RC	Start MRS	End MRS	LFI	Start MCI	End MCI
Scenario 1 (offshore reallocation)	Sediment batch 1	sailing empty to the turning point 1	7 Apr 2018 00:00	7 Apr 2018 00:25	discharging site to turning point	0.42	0	0	0	0	1	0	0
		sailing empty to the port basin 1	7 Apr 2018 00:25	7 Apr 2018 00:28	turning point to the port basin	0.06	0	0	0	0	1	0	0
		loading 1	7 Apr 2018 00:28	7 Apr 2018 01:43	port basin	1.23	1	0	0.67	0	1	0	0
		sailing full to the turning point 1	7 Apr 2018 01:43	7 Apr 2018 01:47	port basin to turning point	0.07	1	0	0.67	0	1	0	0
		sailing full to the discharging site 1	7 Apr 2018 01:47	7 Apr 2018 02:18	turning point to discharging site	0.51	0	0	0	0	1	0	0
		discharging offshore 1	7 Apr 2018 02:18	7 Apr 2018 02:24	discharging site	0.10	0	0	0	0	1	0	0
	...	...	...	...	...	...	...	...	...	...	...	...	
	Sediment batch 79	sailing empty to the turning point 79	15 Apr 2018 19:16	15 Apr 2018 19:41	discharging site to turning point	0.42	0	0	0	0	1	0	0
		sailing empty to the port basin 79	15 Apr 2018 19:41	15 Apr 2018 19:44	turning point to the port basin	0.06	0	0	0	0	1	0	0
		loading 79	15 Apr 2018 19:44	15 Apr 2018 20:58	port basin	1.23	1	0	0.67	0	1	0	0
		sailing full to the turning point 79	15 Apr 2018 20:58	15 Apr 2018 21:20	port basin to turning point	0.07	1	0	0.67	0	1	0	0
		sailing full to the discharging site 79	15 Apr 2018 21:20	15 Apr 2018 21:33	turning point to the discharging site	0.51	0	0	0	0	1	0	0
		discharging offshore 79	15 Apr 2018 21:33	15 Apr 2018 21:39	discharging site	0.10	0	0	0	0	1	0	0
	Scenario 2 (sediment reuse)	Sediment batch 1	Compartment establishment	15 Sep 2017 00:00	7 Apr 2018 00:00	storage compartments	4908.00	1	1	1	0.99	0.39	0.65
sailing empty 1			7 Apr 2018 00:00	7 Apr 2018 00:02	storage compartments to the port basin	0.04	1	0.97	0.99	0.99	0.37	0.67	0.68
loading 1			7 Apr 2018 00:02	7 Apr 2018 01:16	port basin	1.23	1	0.97	0.99	0.99	0.37	0.67	0.68
sailing full 1			7 Apr 2018 01:16	7 Apr 2018 01:20	port basin to storage compartments	0.05	1	0.97	0.99	0.99	0.37	0.67	0.68
discharging 1			7 Apr 2018 01:20	7 Apr 2018 01:53	storage compartments	0.54	1	0.97	0.99	0.99	0.37	0.67	0.68
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Sediment batch 43		sailing empty 43	7 Apr 2018 00:00	11 Jul 2018 00:02	storage compartments to the port basin	0.04	1	0.97	0.99	0.99	0.37	0.67	0.68
		loading 43	7 Apr 2018 00:02	11 Jul 2018 01:15	port basin	1.23	1	0.97	0.99	0.99	0.37	0.67	0.68
		sailing full 43	7 Apr 2018 01:15	11 Jul 2018 01:20	port basin to storage compartments	0.05	1	0.97	0.99	0.99	0.37	0.67	0.68
		discharging 43	7 Apr 2018 01:20	11 Jul 2018 01:53	storage compartments	0.54	1	0.97	0.99	0.99	0.37	0.67	0.68
		Dewatering and ripening	7 Apr 2018 01:53	1 Jan 2022 00:00	storage compartments	32758.12	1	0.97	0.99	0.98	0.35	0.68	0.78
Sediment batch 44		sailing empty 44	11 Jul 2018 00:00	11 Jul 2018 00:02	storage compartments to the port basin	0.04	1	0.94	0.98	0.87	0.35	0.68	0.69
		loading 44	11 Jul 2018 00:02	11 Jul 2018 01:15	port basin	1.23	1	0.94	0.98	0.87	0.35	0.68	0.69
		sailing full 44	11 Jul 2018 01:15	11 Jul 2018 01:20	port basin to storage compartments	0.05	1	0.94	0.98	0.87	0.35	0.68	0.69
	discharging 44	11 Jul 2018 01:20	11 Jul 2018 01:53	storage compartments	0.54	1	0.94	0.98	0.87	0.35	0.68	0.69	
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Sediment batch 79	sailing empty 79	13 Jul 2018 00:00	11 Jul 2018 00:02	storage compartments to the port basin	0.04	1	0.94	0.98	0.87	0.35	0.68	0.69	
	loading 79	13 Jul 2018 00:02	11 Jul 2018 01:15	port basin	1.23	1	0.94	0.98	0.87	0.35	0.68	0.69	
	sailing full 79	13 Jul 2018 01:15	11 Jul 2018 01:20	port basin to storage compartments	0.05	1	0.94	0.98	0.87	0.35	0.68	0.69	
	discharging 79	13 Jul 2018 01:20	11 Jul 2018 01:53	storage compartments	0.54	1	0.94	0.98	0.87	0.35	0.68	0.69	
	Clay transportation	1 Jan 2022 00:00	1 Jan 2023 00:00	storage compartments to the dike	8760.00	1	0.61	0.87	0.87	0.24	0.78	0.78	

Alongside the operational cost and duration of maintenance dredging, the establishment cost and pre-processing time required for the dewatering and ripening of dredged sediments play a crucial role in the decision-making process when selecting an appropriate sediment management strategy. These factors not only determine the economic feasibility of a project but also affect its sustainability performance and resource efficiency. In this context, a trade-off analysis can be conducted to evaluate the relationship between cost, time, energy consumption, and emissions for each scenario, while simultaneously assessing their circularity performance indicators. Such an integrated approach provides a holistic understanding of how each attribute contributes to the overall project outcome. By combining these technical and circularity-based evaluations, decision-makers can identify which strategy achieves the best balance between operational efficiency and environmental benefit.

The radar chart in Figure 5.5 provides a comparative overview of the two dredging scenarios, offshore reallocation (Scenario 1) and sediment reuse (Scenario 2), across multiple performance indicators. Each axis represents a specific attribute, scaled relative to a pre-defined maximum value to preserve the magnitude differences between attributes while maintaining comparability. The chart displays the actual values of each scenario next to the corresponding markers, allowing for immediate visualization of both relative and absolute differences. Scenario 1 exhibits higher cycle costs, energy consumption, and cycle duration, whereas Scenario 2 incurs significant establishment and decommissioning durations, as well as moderate material indices (MRS and MCI). It should be noted that the potential cost associated with the period between the two dredging campaigns is not included in the analysis, as there is no publicly available information on whether the TSHD was demobilized to another project or remained idle. By presenting all key attributes in a single, visually integrated plot, the radar chart effectively highlights trade-offs between the two management approaches, facilitating the interpretation of cost, time, energy, and material quality simultaneously.

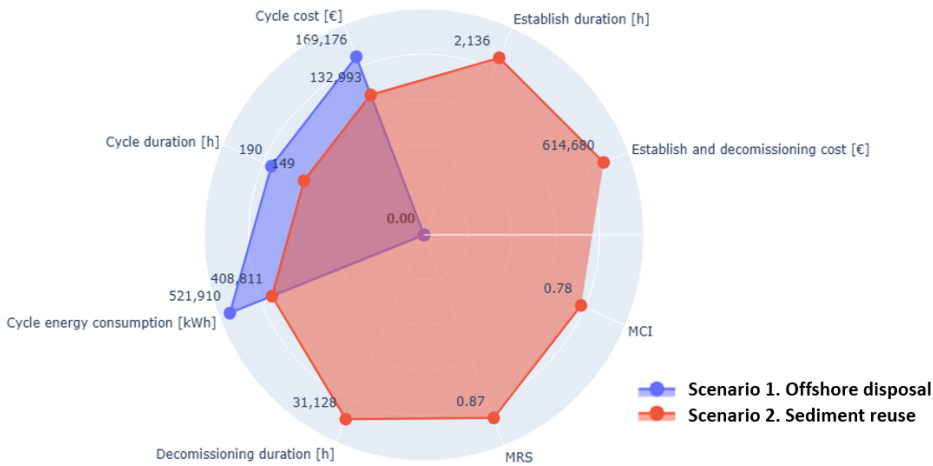


Figure 5.5.: Scenario comparison using a normalized bar chart.

Despite the considerably higher establishment cost and longer duration of Scenario 2 compared to the offshore reallocation alternative, the clay ripening approach demonstrates a substantial contribution to circularity practices. Its enhanced performance in material reuse and circularity indicators (MRS and MCI) underscores its alignment with sustainable port maintenance strategies. Ultimately, the selection between these scenarios depends on multiple project-specific factors such as environmental conditions, regulatory policies, and stakeholder priorities. Decision-makers must weigh the trade-offs between immediate economic costs and long-term environmental benefits, considering aspects like return on investment, ecological impact, and the alignment with broader sustainability goals.

5.4. DISCUSSION

5.4.1. TRANSITION FROM LINEAR TO CIRCULAR PORT MAINTENANCE

The comparative assessment of offshore reallocation and clay ripening scenarios underscores the systemic trade-offs inherent in transitioning from linear to circular dredging practices. While both approaches achieve the operational objective of sediment removal, their broader implications for energy consumption, emissions, and material recovery differ substantially. The results demonstrate that integrating circularity principles into port maintenance requires balancing short-term operational efficiency with long-term environmental and material sustainability.

Scenario 1 (offshore reallocation) confirms the existing linear “extract–use–dispose” model by registering zero for both MRS and MCI indicators. While this scenario achieved the lowest operational and shortest overall dredging time, its approach is environmentally static and represents a missed opportunity for resource recovery. Conversely, Scenario 2 (sediment reuse) explicitly aligns with circular economy principles. Despite the significantly higher establishment cost and a prolonged establishment duration and pre-processing time, it yielded substantial circularity benefits (MRS: 0.87, MCI: 0.78). This contrast highlights the core trade-off: transitioning to circularity demands a higher upfront investment in infrastructure and time, but provides measurable, long-term environmental and resource value. The extended duration of Scenario 2 is primarily driven by the time required for sediment ripening, not operational inefficiency, underscoring that circular strategies may necessitate redefining project timelines to include material transformation phases.

5.4.2. INTEGRATED PERFORMANCE AND TRADE-OFF ANALYSIS

Methodologically, the discrete-event simulation framework employed in this study proves effective for integrating operational parameters, energy dynamics, and circularity indicators into a unified analytical structure. By coupling physical process modeling with circular performance metrics, the approach advances the quantitative assessment of circular economy implementation in marine infrastructure. This framework moves beyond descriptive interpretations of circularity by providing measurable and scenario-specific insights that can support decision-making in port maintenance planning. Furthermore, the adaptation of manufacturing-based indicators such as the MCI to the dredging sector demonstrates the versatility of circularity metrics when properly contextualized to account for dynamic losses, degradation processes, and spatial dependencies.

A crucial finding relates to operational efficiency: Scenario 2 showed a lower operational cost, shorter operational duration, and lower total operational energy consumption compared to Scenario 1's dredging-and-reallocation cycle. This result is primarily attributed to the shorter sailing distance to the near-shore ripening compartments versus the distant offshore reallocation site, illustrating that circular solutions can sometimes improve operational efficiency by optimizing logistics, independent of the circularity outcome itself. This finding emphasizes the need for site-specific assessment, as the trade-off may shift for ports with reallocation sites closer to the dredging area.

The use of MRS and MCI is instrumental in capturing both the quantity (MRS) and the quality/flow (MCI) of material retention, allowing decision-makers to weigh immediate operational gains against regenerative value creation. The MRS of 0.87 for the clay ripening process indicates a high potential for material reuse, while the MCI of 0.78 quantifies the effective closing of the material loop, assuming the ripened clay met a high utility standard ($F(X) = 0.9$) for dike reinforcement.

5.4.3. MANAGERIAL AND RESEARCH IMPLICATIONS

The implications for stakeholders are multifaceted. Decision-makers, such as port authorities, contractors, and environmental agencies, must weigh whether the long-term circular and environmental benefits justify the increased establishment effort and project duration. Such decisions depend on project-specific factors, including sediment characteristics, environmental regulations, available land for sediment treatment, and alignment with broader sustainability objectives. Considering return on investment, policy incentives, and long-term ecological performance can further support a holistic approach to circular port maintenance.

Importantly, circularity is defined within the circular system boundaries, the spatial and temporal limits within which dredged material retention and reuse are considered circular. The definition of these boundaries is inherently subjective and must be established by either the client or the contractor to enable a rational and transparent discussion. For circularity to play a meaningful role in tenders and project proposals, clearly defining both the indicators and the system boundaries is therefore essential. In this specific case, if the client had defined the circular system boundary solely within the aquatic environment, none of the Kleirijperij activities would have been classified as circular. This illustrates that while defining a boundary is necessary

for assessment consistency, allowing contractors to propose alternative or extended boundaries can bring additional circular options into scope, options that the client may not have initially considered. Similarly, setting appropriate time boundaries is crucial, as circular benefits such as sediment ripening, reuse, or degradation processes often manifest beyond the immediate project duration.

From a theoretical perspective, the framework translates abstract circular economy concepts, material loops, resource retention, and value preservation into a process-based assessment method for large-scale infrastructure maintenance. By adapting lessons from the construction sector, the study provides an analytical foundation for circularity in dredging, a field historically lacking appropriate measurement tools.

The current model has limitations that offer avenues for future research:

- Operational and establishment costs are based on publicly available data and charter rates; future work should include detailed cost-benefit analyses, incorporating long-term societal and avoided costs (e.g., reduced flooding risk, avoided contaminant transport, market value of reused material).
- Integrating more realistic physics-based models for power estimation and sediment composition will improve energy, emission, and material loss calculations.
- Expanding the framework to other dredging equipment (e.g., water injection dredgers) and alternative reuse pathways (e.g., habitat restoration, sand-motor nourishment) will increase generality and applicability across diverse port environments.

5.5. CONCLUSION

This study proposed and applied an integrated framework for evaluating circularity in maintenance dredging operations, combining discrete-event simulation with material reuse and circularity indicators. The comparative analysis of two dredging scenarios in the Port of Delfzijl, offshore reallocation and clay ripening, illustrates the operational, environmental, and circular implications of transitioning from linear to circular sediment management practices.

Quantitative results demonstrate that the circular clay ripening scenario achieves a 23% reduction in energy consumption compared to offshore reallocation, while simultaneously attaining high levels of material recovery ($MRS = 0.87$) and circular flow retention ($MCI = 0.78$). Despite higher establishment costs and longer total duration due to sediment pre-treatment and maturation, the scenario provides substantial long-term sustainability benefits through material conservation and reduced offshore reallocation dependence. These findings confirm that circular dredging can transform sediment from a waste by-product into a valuable resource.

The study contributes to theory by operationalizing the principles of circular economy within a process-based modeling framework for hydraulic engineering. Bridges the conceptual gap between the metrics of the circular economy and the temporal-spatial dynamics of dredging operations, enabling a more comprehensive evaluation of material retention and utility over time. Practically, the framework provides a decision-support tool for comparing dredging alternatives based on multi-dimensional performance indicators, facilitating evidence-based policy and project planning toward circular port maintenance.

Future research should extend this approach by incorporating additional dredging techniques and energy transition scenarios, such as the use of low-carbon fuels or hybrid propulsion systems. Integrating environmental and socio-economic indicators, such as ecosystem restoration potential, employment generation, and regional policy alignment, would further enhance the comprehensiveness of circular dredging assessments. Ultimately, the results underscore that realizing circular port maintenance requires not only technological adaptation but also systemic coordination among stakeholders, policies, and infrastructures.

In conclusion, the Port of Delfzijl case exemplifies how circular sediment management can reconcile operational demands with environmental stewardship. By quantifying the interplay between energy, cost, and material reuse, this study provides a replicable methodological foundation for evaluating and advancing circular dredging practices across European and global port systems.

6

DISCUSSION

This chapter discusses the broader implications of the findings presented in this thesis and reflects on the limitations inherent in the research design. The aim is twofold. First, the chapter critically examines the methodological and conceptual choices that shaped the results, including what was done, what could have been done differently, and how these choices influence the validity and broader applicability of the findings. This form of scientific reflection on methods and underlying assumptions is essential for understanding the boundaries within which conclusions can be drawn. Second, the chapter reflects on the contribution of the study despite these limitations, positioning the results within the existing academic and professional discourse on port maintenance, smartness, sustainability, and circularity. The chapter concludes by discussing implications for theory, methodology, and practice.

A central insight throughout this thesis is that smartness, sustainability, and circularity often treated as separate ambitions, are deeply intertwined in practice when making maintenance dredging decisions. Therefore, the discussion focuses not only on the individual methodological components but also on how these components collectively reveal structural relationships between operational efficiency, environmental performance, and sediment reuse opportunities.

6.1. REFLECTION ON RESEARCH METHODS AND UNDERLYING ASSUMPTIONS

To make the value dimensions of smartness, sustainability, and circularity analytically meaningful, the research first relied on a Systematic Literature Review (SLR). This review required several methodological assumptions, including the selection of the Frame of Reference (FoR) approach to delineate the scope of relevant studies and the choice to distinguish between port authority and contractor perspectives as the dominant viewpoints in maintenance dredging decision-making. While these choices provided a coherent framework for interpreting how the three value dimensions are understood in practice, they also inevitably excluded alternative perspectives and disciplinary framings. Building on this conceptual foundation, the subsequent methodological steps made the abstract concepts tangible through quantification: Automatic Identification System (AIS) data were used to analyze navigational interference, discrete-event simulation supported the operational and emission modeling, and product-based circularity indicators (Material Re-utilization Score (MRS)/Material Circularity Indicator (MCI)) were adapted for sediment-reuse assessment. Together, these methodological choices shaped how smartness, sustainability, and circularity could be operationalized within the scope of this thesis. These choices, while enabling quantification, introduce specific limitations that warrant some critical points summarized as follows.

- **Literature review design and conceptual framing**

The conceptualization of smartness, sustainability, and circularity in this thesis was shaped by the SLR and the use of the FoR approach to organize a diverse and fragmented body of research. While this approach provided a consistent framework, its general structure also constrained the scope of the review by emphasizing the dredging work method engineering domains over others. As a result, potentially relevant insights from fields such as behavioral sciences, maritime governance, or organizational studies may have been overlooked. For example, behavioral studies on pilot and harbor master decision-making under operational constraints could have helped explain why similar dredging-seagoing traffic interactions lead to different levels of disruption in practice. A similar limitation applies to the stakeholder framing adopted in the review. By focusing primarily on port

authorities and dredging contractors, the analysis captured the two dominant decision-making actors but did not account for the perspectives of pilots, terminal operators, harbor masters, regulators, non-governmental organizations, or end-users of dredged materials. These actors influence port operations and sediment-management decisions in ways that fall outside the chosen analytical lens. Together, these simplifications were necessary to maintain clarity and coherence in the review, yet they also narrow the conceptual boundaries of the thesis. Future research could benefit from broader classification schemes and a more diverse set of stakeholder viewpoints to enrich the interpretation of these value dimensions.

- **Data availability and representativeness**

The smartness assessment in this study is grounded in the qualification of interactions between seagoing traffic and maintenance dredging activities, using AIS-based reconstructions of vessel movements as a proxy for operational interference. The analysis relied on AIS data derived from a single year, a single port, and a specific class of dredging vessels, which inevitably restricts the representativeness of the findings. While AIS provides a powerful means to reconstruct vessel positions and infer potential interactions, it offers only a partial view of port operations. Critical components of port logistics, such as berth occupancy, pilot dispatching, terminal planning, and weather-related maneuvering constraints, remain unobserved in AIS datasets. Consequently, some interactions identified as dredging-related interference may also be influenced by other operational factors that are not explicitly captured in the data. In addition, AIS data quality is not uniform across vessels and operational contexts. Variations in reporting intervals, temporary signal loss in congested port areas, or the use of different transponder classes can reduce the ability to detect very short-term or fine-scale interactions, such as brief speed reductions or localized maneuvering adjustments. These limitations do not invalidate the analysis but indicate that some subtle interference effects may remain unresolved. Taken together, these constraints limit the extent to which the smartness results can be generalized and highlight the need for future research to integrate multi-year, multi-port, and multi-source datasets, including traffic management, pilotage, and meteorological information, to achieve a more comprehensive assessment of operational interaction.

- **Simplification in emission modeling**

The sustainability assessment relied on assumed engine load profiles and idealized dredging cycles, with constant engine load settings per event. In reality, engine loads vary within events due to operational and environmental fluctuations, meaning that intra-event variability in emissions is not captured, and results represent averaged behavior. Real-world dredging operations show substantial variability in fuel use due to differences in sediment density, pump wear, operational strategies, equipment maintenance, pipeline resistance, and site-specific hydrodynamic conditions. Although onboard fuel-flow measurements or high-frequency engine telemetry were unavailable, a validation was conducted by comparing simulated Water Injection Dredger (WID) fuel use with vessel log data, showing consistent magnitudes and trends. However, broader validation using high-resolution, multi-vessel datasets is still required. Consequently, the absolute emission values should be interpreted with caution, although the relative comparison between Trailing Suction Hopper Dredger (TSHD)s and WIDs remains meaningful within the modeling assumptions. These simplifications highlight the need for future studies to incorporate sensor-based validation and high-resolution operational monitoring.

- **Constraints in the circularity assessment**

The circularity assessment was based on a single reuse case for dike reinforcement, supported by limited geotechnical testing and several design assumptions. While the circularity indicators are highly sensitive to local sediment, ecological, and regulatory conditions, making the resulting values case-specific, the assessment framework itself is transferable and can be applied to other ports with appropriate contextualization. The absence of field trials, long-term performance data, and coordination with water authorities also leaves uncertainties regarding consolidation, durability, environmental safety, and required quality control. Furthermore, real-world feasibility depends on aligning dredging and construction timelines, an organizational factor beyond the scope of this study. Despite these limitations, the case study demonstrates what is now possible: linking operational dredging data with MRS/MCI indicators to create a quantifiable and transferable approach for evaluating circular sediment applications. This provides a practical analytical framework that others can adapt, even though the specific results remain illustrative rather than universal.

- **Integrating limitations between smartness, sustainability, and circularity**

This thesis develops a combined framework for evaluating maintenance dredging strategies across smartness, sustainability, and circularity dimensions. Yet the integration remains partly conceptual, and several limitations undermine the scope of the analysis. A key challenge is that the indicators operate on different timescales, short-term operations, medium-term activities, and long-term strategies, making quantitative coupling difficult. Although the event-table approach enables linking operational phases to higher-level performance metrics, the present implementation uses fixed event definitions and does not yet explore feedback, scenario variability, or multi-cycle accumulation effects.

The methodology also relied on simplifying assumptions. The discrete-event perspective used in the smartness analysis excludes hydrodynamic and morphodynamic processes that directly affect accessibility. The emission model treats engine performance deterministically and neglects operational uncertainties, including the influence of environmental conditions such as currents and their effect on sailing resistance. The circularity assessment focuses on geotechnical feasibility, without considering ecological risks or long-term structural performance. Each of these choices narrows the interpretation of results and highlights the partial nature of the system representation.

Furthermore, the framework reflects mainly contractor and port authority perspectives, leaving out other stakeholders, such as regulators, terminal operators, shipping lines, and local communities, whose value functions may differ substantially. Interactions between Key Performance Indicator (KPI)s, such as how reduced interference lowers emissions or how circularity alters sailing distances, were not modeled quantitatively.

Future work should therefore widen the analysis both methodologically and discipline-wise. Opportunities include coupled hydro-morphodynamic simulations, stochastic engine models, and full life-cycle circularity assessments, alongside broader stakeholder integration. Such extensions would refine the framework, strengthen its validity, and enhance its capacity to inform sustainable and circular port maintenance strategies.

6.2. REFLECTIVE POSITIONING AND MAIN CONTRIBUTIONS

Acknowledging these limitations clarifies what claims can and cannot be made. Despite the constraints, the thesis offers several contributions that address gaps in both academic literature and port maintenance practice.

- **Clarifying value dimensions through SLR/FoR framing**

By starting from a SLR and FoR approach, the thesis contributes to the literature by unpacking broad value dimensions such as smartness, sustainability, and circularity into engineering dimensions. This framing not only highlights how these concepts have been treated abstractly in prior work, but also translates them into decision-making contexts where different stakeholders may apply distinct criteria. In doing so, the thesis shows that value dimensions which are commonly addressed conceptually or qualitatively in the literature can also be assessed quantitatively, enabling a more explicit comparison between the perspectives of port authorities and contractors.

- **Advancing quantitative understanding of smart port maintenance**

Despite the limitations of the AIS-based analysis, the thesis demonstrates that smartness, often treated as an abstract ambition, can be operationalized through real-world data. While Bakker *et al.* (2024) quantify cascading accessibility effects among seagoing vessels driven by tidal and depth constraints, interactions between maintenance dredging vessels and commercial traffic are not explicitly included. This thesis extends that line of work by explicitly quantifying how maintenance dredging operations interact with regular port traffic, showing how such interactions can be measured, visualized, and compared across operational scenarios. This thesis adds a new empirical dimension to the field by showing how disruptions can be measured, visualized, and compared across operational scenarios. Even though the analysis is bound to a single port, the demonstrated method provides an approach that can be applied at other ports and scaled to multi-year datasets. In this way, the research contributes a workable pathway for moving smart maintenance from a conceptual idea to a data-driven practice.

- **Introducing a structured and comparable sustainability assessment for dredging**

The sustainability dimension provides one of the first consistent, energy footprint and CO₂ emission profiles for TSHD and WID dredging in an operational port context. Existing literature often reports aggregate emissions or general fuel intensities, but rarely provides detailed breakdowns per dredging stage or examines how operational choices influence emissions. Although based on simplified load assumptions, the results in this thesis highlight which components of a dredging cycle dominate fuel consumption and where environmental efficiencies can be achieved. This structured approach allows contractors and port authorities to compare strategies, justify equipment choices, and anticipate environmental performance, capabilities not fully supported by existing frameworks in the literature. In addition, by linking emission profiles directly to operational choices, the method enables rational and transparent discussions: client demands (e.g., maximum emission thresholds) can be explicitly shown in terms of their operational consequences, while potential mitigating measures can be evaluated for their concrete project-level impacts. This transparency, ensuring that no sustainability statements remain abstract but are demonstrably tied to operational realities, represents a novel contribution to the literature.

- **Operationalizing circularity in a technically grounded manner**

Circularity in sediment management is commonly treated at a conceptual level, with calls for beneficial reuse, but it offers limited guidance on evaluating feasibility. By applying geotechnical analyses, logistical reasoning, and comparative KPI-based assessment, the thesis translates circularity into measurable performance indicators. Even though the circularity case study focuses on a single application, it shows how engineering, environmental, and logistical considerations can be integrated to determine whether reuse is viable. This represents a step forward from abstract circularity principles toward concrete, decision-ready evaluation methods. It also directly addresses the concern raised in Chapter 1 that dimensions such as smartness, sustainability, and circularity have often remained insufficiently clear, which hinders their adoption in practice. Many existing frameworks and guidance documents, including beneficial-use guidance from organizations such as Laboyrie *et al.* (2018), discuss smartness, sustainability, and circularity primarily at a conceptual or strategic level. By unpacking these container terms into measurable, engineering dimensions, this thesis demonstrates how they can be translated into transparent evaluation frameworks. In doing so, the research not only clarifies previously ambiguous notions but also provides stakeholders with tools that support consistent comparison, negotiation, and strategic decision-making.

- **Demonstrating the interconnectedness of smartness, sustainability, and circularity**

One of the thesis's key conceptual contributions is the empirical demonstration that these three value domains mutually influence each other. The analysis shows that operational efficiency can influence emissions; emissions influence the perceived value of reuse pathways; and circularity ambitions can affect sailing distances and planning constraints. This interdependence has not been widely recognized in the literature, where these themes are typically addressed in isolation. By quantifying each dimension and applying it to consistent case studies, the thesis reveals structural relationships that provide a foundation for more integrated theoretical models and strategic maintenance planning tools.

Although the integrated framework presented is not yet fully quantitative, it offers a coherent structure through which smartness, sustainability, and circularity can be compared for any port maintenance strategy. This fills a methodological gap in both academic literature and professional practice, where decision-making tools commonly focus on a single value (e.g., cost, accessibility, or environmental impact). By placing all three domains into a comparable KPI framework, this thesis opens the door to multi-objective optimization, digital twin integration, and more transparent procurement processes. Even with its limitations, the framework marks an important step toward holistic, future-oriented port maintenance.

6.3. IMPLICATIONS

- **Theoretical implications**

The findings of this thesis contribute to several theoretical developments in the domains of port maintenance, infrastructure governance, and sediment management. First, the results demonstrate that smartness, sustainability, and circularity, typically conceptualized as separate ambitions, are deeply interdependent when examined empirically. This challenges theoretical frameworks that treat them as isolated optimization problems and highlights the need for integrated multi-value models. The results

of this thesis show instead that operational decisions designed to improve accessibility may influence fuel use, environmental footprint, and even the availability of material for circular applications. This interdependence suggests that future theoretical work should move toward conceptual models that connect operational dredging activities with project-level and port-level performance, and that consider multiple objectives simultaneously rather than separately.

Second, the thesis advances the emerging theoretical discourse on circular sediment management. Circularity in dredging is often framed conceptually, through notions of resource loops, material stewardship, or beneficial reuse, but the corresponding open literature lacks operational definitions and quantifiable indicators. This thesis shows that circularity can be assessed in practical terms—through geotechnical, logistical, and environmental criteria, rather than remaining a purely normative ambition.

Finally, the findings indicate that the concept of “optimal maintenance strategy” is poorly defined in current literature. In practice, maintenance decisions involve balancing values that cannot be collapsed into a single KPI or economic metric. This supports a shift in theoretical understanding from single-objective optimization to multi-value decision contexts, where the meaning of “optimal” is contingent on stakeholder priorities, temporal scales, and environmental constraints. Such a shift aligns port maintenance theory with contemporary debates on sustainable and circular infrastructure systems.

- **Methodological implications**

The methodological implications of this thesis center on the need for more integrated, validated, and multi-source approaches to evaluating port maintenance strategies. First, the research demonstrates the value of combining AIS data, emission modeling, and circularity assessments into a single evaluative structure. This multi-method approach is more representative of real-world decision-making than traditional analyses, but also reveals limitations in current tools and datasets. For instance, integrating AIS data with terminal berth occupancy, hydrographic surveys, and fuel-flow measurements would significantly improve the fidelity of smartness and sustainability assessments. The methodological implication is that future studies should combine event-based vessel movements data and dredging activity logs with multi-year environmental datasets describing sedimentation patterns and hydrodynamic variability, enabling predictive assessment of maintenance strategies beyond single-project or single-cycle analyses.

Second, the results highlight the necessity of enhanced modeling techniques. The emission assessment used deterministic assumptions about engine loads and pump behavior, while the smartness analysis relied on historical AIS data without dynamic modeling of vessel interactions. Future methodological development should therefore focus on simulation-based approaches, such as coupled accessibility–emission simulations, agent-based multi-vessel interaction models, or hybrid discrete-event and hydrodynamic simulations. These approaches would allow researchers to test alternative operational choices and quantify the resulting trade-offs between accessibility, emissions, and project duration.

Third, the analysis reveals the importance of validation and uncertainty quantification. Uncertainty in sediment properties, fuel consumption rates, and environmental conditions can propagate through the analyses and influence the ranking of dredging strategies. Future methodological work should include structured uncertainty analysis, stochastic modeling, and sensor-based validation, allowing for more robust and transferable findings. This would move port maintenance research toward more transparent and evidence-driven methodological standards, aligning with trends in maritime digitization and environmental monitoring.

Fourth, the thesis demonstrates the methodological potential of making diverse perspectives and disciplinary information combinable. By mapping different stakeholder viewpoints onto the same FoR elements, the research shows how smartness, sustainability, and circularity can be compared within a consistent evaluative structure, an approach not previously seen in the maintenance dredging literature. Moreover, the use of discrete-event simulation in combination with the event table enables attributes beyond time and cost (such as emissions, reuse feasibility, or operational constraints) to be attached to events. This methodological innovation allows information from different disciplines to be integrated, compared, and combined more effectively, thereby supporting rational negotiation and multi-criteria decision-making. Future work could expand this approach by incorporating additional stakeholder dimensions and testing how combinability functions across varied port contexts.

- **Managerial implications**

The implications of this thesis are intended to support real-world decision-making by port authorities, contractors, and regulatory bodies, spanning operational planning, managerial coordination, and strategic policy formulation. First, the findings provide actionable insights for improving the planning and execution of maintenance dredging. By quantifying how dredging affects vessel accessibility, the smartness analysis offers a data-driven foundation for adjusting working windows, coordinating traffic, or modifying fairway layouts. Ports can use these insights to reduce delays, optimize tidal windows, and design strategies that minimize disruption to commercial operations, while explicitly accounting for how such decisions affect dredging operations and their execution.

Second, the sustainability assessment gives practitioners a transparent breakdown of emissions across the dredging cycle, enabling more informed decisions about fleet selection, operational modes, and environmental compliance. This is particularly relevant in a regulatory environment where emission reporting and reduction targets are tightening. Contractors can use the results to fine-tune pump operations or adopt speed optimization strategies, while port authorities can use the findings to set environmental performance standards or incentivize low-emission dredging.

Third, the circularity analysis provides a structured framework for evaluating sediment reuse opportunities by explicitly addressing circularity boundaries in space and time. The case study shows that circular applications such as dike reinforcement are technically feasible, but only when dredging schedules, sediment quality, and infrastructure project timelines are aligned within clearly defined system boundaries that determine whether circular performance is assessed at the scale of a maintenance campaign, a port system, or a wider regional network. From a managerial perspective, these boundaries should be made explicit early in the decision-making process: port and water authorities can specify them as part of strategic objectives and policy frameworks, while dredging contractors can proactively propose feasible boundary definitions based on operational and logistical constraints. Explicit agreement on circularity boundaries enables early coordination between maintenance and capital projects, reduces uncertainty and unnecessary sediment reallocation, and supports the creation of new value streams from dredged sediments, while also providing a clearer basis for regulation and long-term monitoring.

Finally, the integrated framework offers practitioners a more holistic way of assessing maintenance strategies. Instead of selecting strategies based solely on cost or operational convenience, ports can now evaluate trade-offs across smartness, sustainability, and circularity, revealing options that may have been overlooked under traditional decision-making processes. This supports a shift toward strategic, future-oriented port maintenance that aligns with societal goals of de-carbonization, resource circularity, and resilient infrastructure development. It also directly responds to the challenges outlined in Chapter 1: clients often articulate demands (e.g., emission limits or accessibility requirements) without fully grasping their operational consequences, while contractors may propose innovations without demonstrating project-level impacts. By making these consequences transparent and quantifiable, the thesis provides a bridge between abstract ambitions and concrete operational realities, enabling more rational negotiation and evidence-based decision-making across stakeholders.

7

CONCLUSIONS AND RECOMMENDATIONS

This chapter concludes the thesis by synthesizing the main findings and presenting recommendations for future research. The structure follows the progression from problem statement to research objective and from sub-questions to the overarching main question. The chapter ends with several concrete directions for advancing research and strategies on smart, sustainable, and circular port maintenance.

7.1. REFLECTION ON PROBLEM STATEMENT AND RESEARCH OBJECTIVE

Port maintenance dredging is essential for ensuring navigational accessibility, but decision-making remains fragmented across three frequently incompatible ambitions: operational efficiency (“smartness”), environmental performance (“sustainability”), and beneficial reuse of sediments (“circularity”). Existing frameworks and tools typically address these ambitions in isolation, do not quantify trade-offs holistically, and often lack the operational detail needed for strategic decision-making. This fragmentation leads to suboptimal maintenance strategies, insufficient understanding of emissions and disruptions, and underdeveloped pathways for circular sediment reuse.

The objective of this thesis was to develop and apply a framework that quantitatively and qualitatively evaluates maintenance dredging strategies from three complementary value dimensions (smartness, sustainability, and circularity) to support more integrated and informed decision-making in port maintenance.

7.2. ANSWERING RESEARCH QUESTIONS

The following sub-questions are answered in this study. Along with answering the sub-questions, a simplified anatomy of events is summarized in a single table categorizing the problem based on vessel ID, activities, timestamps, and attributes.

1. How are smartness, sustainability, and circularity defined in the literature and interpreted by port authorities and contractors?

The results obtained in Chapter 2 show that contractors and port authorities broadly agree on the importance of these three values but differ in how they prioritize and operationalize them. Contractors emphasize predictability, cost, and workflow efficiency, while port authorities focus more on navigational reliability, stakeholder coordination, and long-term environmental responsibilities. Circularity is generally understood conceptually, but concrete performance indicators are lacking. The analysis reveals that ambiguity in definitions, particularly regarding smartness and circularity, leads to misalignment in expectations. The Frame of Reference (FoR) coupled with a Systematic Literature Review (SLR) provides a useful structure for categorizing perspectives, but without quantified Key Performance Indicator (KPI)s, it remains too abstract for operational decision-making. This finding underscores the need for clearer, more measurable definitions that enable comparison across dredging strategies.

2. How can smart, data-driven methods quantify the interaction between seagoing processes and maintenance dredging?

Smartness was operationalized in Chapter 3 by analyzing the interactions between dredging operations and vessel traffic using Automatic Identification System (AIS) data. The analysis showed that even small-sized ports experience measurable disruptions when dredgers operate within constrained

fairways, especially during peak tidal windows. The empirical approach revealed patterns of interference that are not visible through traditional planning tools. The results further demonstrate that smartness is not solely a function of dredging duration or capacity but also of spatial and temporal coordination with commercial vessel movements. This approach shows how AIS-based analyses can incorporate maintenance dredging into accessibility assessments. While demonstrated for one port and dataset, the method opens the possibility to compare dredging work methods with respect to how they interfere with, or avoid interference with, regular port operations, such as the application of Water Injection Dredger (WID) to reduce operational disruption. Table 7.1 explicitly builds on the insights from Chapter 3, in which the AIS-derived interference analyses (Figures 3.3 and 3.4) and Gantt-based (Figure 3.5) event timelines revealed how dredging operations influence port accessibility and vessel waiting times.

Table 7.1.: Event-based representation of Trailing Suction Hopper Dredger (TSHD) and WID vessels used to quantify smartness.

Vessel ID	Events	Timestamp	Attributes
TSHD	sailing, dredging, placement, waiting	event start – event stop	location
Dry bulk vessel	arriving, berthing, departing, waiting	event start – event stop	location

3. How can the sustainability impacts of maintenance dredging equipment selection be quantified?

The modeling of energy footprint and CO₂ emissions for different dredging stages has shown substantial variation between TSHD and WID operations in Chapter 4. Dredging and transport phases dominate total emissions for TSHDs, whereas WIDs exhibit lower overall emissions. The analysis provides a phase-specific breakdown of emissions across the dredging cycle, showing that strategic operational adjustments, such as speed optimization or modified pumping regimes, can meaningfully influence environmental performance. Although the model relies on assumed engine loads and limited validation, the relative differences between vessels are robust. The findings contribute to the literature by providing a structured, comparable emission breakdown for different types of maintenance dredging, enabling more informed, sustainability-oriented decision-making. Table 7.2 builds on the analyses presented in Chapter 4, where the physics-based power and emission estimations, heatmaps (Figure 4.2), and event-level comparisons between WID and TSHD operations (Figures 4.4 and 4.3) quantified the time–emissions trade-offs that underpin the indicators summarized here.

Table 7.2.: Event-based representation of TSHD and WID vessels used to quantify sustainability.

Vessel ID	Events	Timestamp	Attributes
TSHD	sailing, dredging, placement, waiting	event start – event stop	location, power consumption, energy consumption, CO ₂ emission
WID	sailing, dredging, waiting for ebb tide	event start – event stop	location, power consumption, energy consumption, CO ₂ emission

4. How can the circularity aspect of sediment-reuse strategies be quantified and distinguished from traditional linear maintenance methods?

The circularity case study presented in Chapter 5 demonstrated that reusing dredged sediments for dike reinforcement is technically feasible under specific conditions and can reduce offshore reallocation volumes, transport distances, and associated emissions. The evaluation framework translated circularity from a qualitative ambition into quantifiable geotechnical, logistical, and environmental indicators. However, the analysis also revealed significant bottlenecks: uncertainty in sediment properties, risk of contaminants, mismatched project timelines, and regulatory complexity. Compared to traditional maintenance dredging strategies, circular strategies introduce additional system complexity that requires more coordination among stakeholders. Equally important, the study highlights that circularity cannot be meaningfully assessed without clear spatial and temporal boundaries: only by defining where reuse occurs and when material flows align with project needs can circularity be distinguished from conventional reallocation. Nonetheless, the study shows that circularity can be meaningfully integrated into port maintenance planning when supported by robust technical evaluation and early-stage feasibility assessments. Table 7.3 builds on the analyses presented in Chapter 5, where the circular system boundaries, event-based comparison of offshore disposal and beneficial reuse scenarios (Figures 5.2 and 5.3), and the calculation of circularity indicators (Figure

5.4 demonstrated how spatial configuration, vessel characteristics, and reuse pathways shape circular performance outcomes.

Table 7.3.: Event-based representation of linear and circular maintenance scenarios used to quantify circularity.

Vessel ID	Events	Timestamp	Attributes
TSHD (linear)	sailing, dredging, placement	event start – event stop	location, power consumption, energy consumption, CO ₂ emission, circularity indicators
TSHD (circular)	sailing, dredging, pipeline transport	event start – event stop	location, power consumption, energy consumption, CO ₂ emission

Answering the sub-questions leads us to answer the main research question of this study as follows.

- **Main research question: How can smart, sustainable, and circular strategies be made quantifiable to support trade-off analyses and informed selection of port maintenance strategies?**

This thesis demonstrates that joint evaluation of maintenance dredging strategies is possible by developing a structured framework that operationalizes each value dimension through quantifiable indicators and applies them consistently across realistic case studies. Smartness is evaluated through AIS-based assessments of operational interference and waiting behavior; sustainability through stage-based CO₂ emission modeling of dredging cycles; and circularity through a feasibility assessment of sediment reuse in dike reinforcement. By structuring these analyses at the level of discrete operational events, the framework captures the essential characteristics of different maintenance strategies consistently and comparably. The event-based representation plays a central role in answering the main research question.

By decomposing dredging and seagoing processes into events, the analysis makes explicit who waits for whom in smart port maintenance, how different vessel types such as TSHDs and WIDs compare in terms of energy use and emissions, and how circular reuse scenarios differ from linear disposal strategies. Because all results are stored within a unified event table, the framework allows flexible filtering and aggregation: individual events can be inspected, values can be aggregated per vessel or per dredging cycle, and overall performance can be evaluated at the project level. This flexibility enables decision-makers to move seamlessly between detailed operational insight and high-level strategic comparison.

The main research question of this dissertation can be addressed through the combined interpretation of Tables 7.1, 7.2, and 7.3. Rather than providing a single aggregated metric, the research demonstrates that answering this question requires the integration of complementary perspectives on maintenance dredging strategy selection. Each table captures a distinct but interdependent value dimension, and only by considering them together can the full implications of alternative strategies be assessed. This combined reading enables trade-offs to be made explicit and supports a comprehensive, transparent comparison of maintenance dredging strategies, consistent with the multi-dimensional framework developed in this thesis.

The central conclusion of this thesis is that smart, sustainable, and circular port maintenance are inherently interconnected dimensions. The analyses show that optimizing a single aspect in isolation, whether accessibility, emissions, or sediment reuse, can lead to unintended or undesired outcomes in other domains. The event level is shown to be the most appropriate level of analysis for maintenance strategies, as it aligns with how such strategies are executed in practice and how decision-makers typically compare alternatives. Consequently, maintenance strategies should be evaluated in an integral manner, where trade-offs across smartness, sustainability, and circularity are considered jointly. This thesis provides a foundational methodology for such evaluation, demonstrating both its feasibility and its practical relevance.

7.3. RECOMMENDATIONS FOR FUTURE RESEARCH

The findings of this thesis point toward several avenues for further research that could significantly advance smart, sustainable, and circular port maintenance. The recommendations below emphasize methodological, operational, and strategic developments and propose specific actions that future researchers can undertake.

- **Expand toward a multi-stakeholder decision framework.**

Future research should incorporate a broader set of stakeholders, such as terminal operators, shipping lines, pilots, environmental regulators, and local communities, to better capture the full range of values influencing maintenance dredging decisions. While this thesis focused primarily on contractors and port authorities, adding multiple perspectives can reveal conflicting priorities around accessibility, emissions, and sediment reuse. Methods such as Multi-Criteria Decision Analysis (MCDA), discrete choice modeling, or stakeholder value mapping could formalize these preferences and integrate them into the smartness, sustainability, and circularity framework, thereby enhancing transparency and supporting more robust and equitable decision-making across the port system.

At the same time, the practical uptake of smart, sustainable, and circular strategies depends heavily on institutional arrangements, procurement formats, and contractual incentives. Future research should therefore examine how performance-based contracts, value-based tendering, early contractor involvement, or long-term maintenance agreements influence the adoption of integrated strategies. Analyzing how the KPIs developed in this thesis could be embedded into tender documents, regulatory guidelines, or port master plans would help translate technical insights into actionable governance reforms, supporting a transition from cost-driven to value-driven maintenance procurement and strengthening alignment between operational practice and societal goals.

- **Advance smartness through dynamic and predictive modeling.**

Future research should further advance the smartness dimension by developing dynamic models that go beyond retrospective AIS-based analyses. While this thesis demonstrated how disruptions can be quantified and visualized, future work could integrate real-time AIS streams with berth occupancy data, tidal forecasts, and vessel scheduling systems to create predictive tools for operational planning. Such models would allow ports to anticipate accessibility bottlenecks before they occur, test alternative traffic management strategies, and evaluate the resilience of fairway layouts under varying demand scenarios. Linking smartness assessments to digital twin environments could also provide decision-makers with interactive platforms to explore counterfactuals and optimize maintenance strategies in a proactive rather than reactive manner.

- **Validate sustainability assessments with empirical measurements.**

A major next step is validating emission estimates through real-world fuel and power measurements. While modern TSHDs and WIDs are already equipped with fuel-flow meters, shaft power sensors, and pump efficiency logging systems, the resulting datasets are not yet systematically available for research and comparative analysis. Future work should therefore focus on improving access to and integration of these operational measurements, enabling detailed assessments of energy use under varying sediment and operational conditions. Such transparency would allow emission modeling and efficiency evaluations to move beyond simplified assumptions toward evidence-based, project-level insights.

Comparing these measurements with model-based estimates would help refine emission factors, capture operational variability, and improve accuracy for port-specific emissions reporting. Such validation would also support regulatory compliance, aid in environmental certification processes, and provide a stronger empirical foundation for comparing dredging strategies and identifying opportunities for carbon reduction. However, a critical challenge is that contractors do not typically make detailed operational datasets publicly available, which limits the extent to which independent validation can currently be performed. Future progress will therefore depend not only on methodological advances but also on institutional arrangements and data-sharing agreements that enable transparent access to the measurements already being collected onboard dredging equipment.

- **Extend circularity assessments to full life-cycle and long-term impacts.**

Circularity calculations would benefit from a broader life-cycle perspective that considers long-term environmental, technical, and societal impacts. Future research could integrate life-cycle assessment, geochemical modeling, and long-term monitoring data to evaluate the durability, ecological performance, and carbon footprint of sediment reuse applications such as dike reinforcement, land reclamation, or habitat creation. Incorporating life-cycle cost-benefit analysis and risk assessments would reveal the true long-term value and sustainability of circular strategies compared to offshore

reallocation. This expanded perspective would strengthen regulatory acceptance, help identify optimal reuse pathways, and contribute to a more holistic understanding of circular sediment management.

- **Integrated modeling, digital twins, and sediment dynamics**

Future research should advance the methodological foundations of smart, sustainable, and circular port maintenance by developing integrated simulations and digital twin environments. Such systems could jointly model accessibility, emissions, and sediment reuse scenarios by linking AIS traffic data, hydrographic surveys, pump telemetry, and tidal forecasts into unified, dynamic simulations. Building on the KPIs established in this thesis, multi-objective optimization techniques, such as Pareto analysis, evolutionary algorithms, or multi-criteria decision frameworks, could be applied to generate efficient dredging strategies under varying stakeholder priorities.

Incorporating stochastic modeling of tides, weather, sedimentation, and operational uncertainties would further strengthen robustness and allow ports to identify strategies that balance conflicting objectives. At the same time, future work should integrate dredging operations with morphodynamic models to capture how dredging frequency, depth, and material placement influence long-term sediment behavior. Coupling operational dredging models with hydrodynamic and morphological simulations would provide deeper insight into feedback between environmental processes and maintenance needs, enabling more forward-looking planning and reducing long-term dredging demand. Together, these advances would make complex trade-offs more interpretable for practitioners, support both day-to-day operational planning and long-term strategic assessments, and bridge the gap between theoretical frameworks and practical decision-making.

7.4. FINAL REFLECTION

This thesis has shown that smartness, sustainability, and circularity, traditionally treated as separate concerns, are intrinsically linked in port maintenance. By developing a framework that integrates empirical operational data, environmental modeling, and circularity assessment, the research contributes to a more holistic understanding of maintenance dredging. While significant work remains to sharpen and validate the methodological components, the results point toward a future in which port maintenance strategies can be evaluated not only for their immediate effectiveness but also for their long-term contribution to sustainable and circular port development.

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NOMENCLATURE

- AI** Artificial Intelligence. 19, 20, 27
- AIS** Automatic Identification System. vii, 20, 21, 31–38, 71–73, 75, 77–81, 119
- BHD** Back Hoe Dredger. 4, 5, 37
- BL** Bed Leveler. 4, 5
- CE** Circular Economy. 56
- CEDA** Central Dredging Association. 15
- FoR** Frame of Reference. vii, 11–16, 19, 21, 24, 26–29, 71, 73, 75, 77
- GD** Grab Dredger. 4, 5, 32, 37
- HEE** High Energy Environment. 44, 47, 116, 117
- IADC** International Association of Dredging Companies. 15
- KPI** Key Performance Indicator. 10, 28, 29, 73–75, 77, 80, 81
- LEE** Low Energy Environment. 44, 47, 49, 116, 117
- MBL** Maintained Bed Level. 2
- MCDA** Multi-Criteria Decision Analysis. 23, 29, 80
- MCI** Material Circularity Indicator. 55, 56, 59, 60, 65, 67–69, 71, 72
- MRS** Material Re-utilization Score. 55, 59, 65, 67–69, 71, 72
- PoR** Port of Rotterdam. 7, 26, 32, 33, 38
- SLR** Systematic Literature Review. vii, 11–16, 19, 21, 24, 26–29, 71, 73, 77
- SURICATES** Sediment Use as Resource In Circular And Territorial Economies. 25
- TDS** Tons Dry Solid. 60, 65
- TSHD** Trailing Suction Hopper Dredger. 4, 5, 9, 19, 20, 22, 23, 25, 26, 32–38, 41–47, 49, 50, 52, 53, 56, 57, 59, 62, 64, 67, 72, 74, 78–80, 99, 100, 107–109, 111, 112, 114–116
- UKC** Under Keel Clearance. 2, 3
- WID** Water Injection Dredger. 5, 9, 26, 37, 41–47, 49–53, 72, 74, 78–80, 99, 100, 111, 116, 117
- WODA** World Organization of Dredging Associations. 15
- WODCON** World Dredging Congress. 15

A

APPENDIX A

This appendix provides an overview of the estimation models used to calculate the power consumption of both Trailing Suction Hopper Dredger (TSHD) and Water Injection Dredger (WID) vessels. The power on board is distributed across several key energy consumers, such as propellers, pumps, thrusters, and electrical systems, each serving specific operational functions. These consumers are summarized below.

- **Propulsion system:** The propulsion systems of TSHDs and WIDs are designed to deliver adequate power and maneuverability during dredging and material transport. TSHDs typically use high-capacity diesel engines that drive conventional propellers, operating at full power during sailing and at reduced levels during loading and unloading. Inboard dredge pumps inside the hull generate suction to transport sediments into the hopper and may be combined with underwater pumps to increase pumping capacity or distance; they also support material discharge via bottom doors or pipelines. By contrast, WIDs depend on precise positioning to make use of natural currents for sediment transport. Their propulsion usually consists of diesel-driven propellers, sometimes supplemented by electric drives for improved fuel efficiency and reduced emissions. Although propellers remain active throughout dredging, their overall energy consumption is relatively low due to slow operational speeds.
- **Dredge pumps:** Submersible dredge pumps are mounted outside the hull of a TSHD, typically near the draghead at the end of the suction pipe. Unlike inboard pumps, they provide additional suction power directly at the seabed, helping overcome increased loads at greater depths and enabling the transport of denser or more concentrated material.
- **Jet pumps:** Jet pumps mobilize sediments through pressurized water jets. In TSHDs, high-pressure jets integrated into the draghead loosen compacted seabed materials, such as clay, silt, or sand, facilitating suction and reducing the risk of pipeline clogging. They can also be used to fluidize material in the hopper or assist during discharge. For WIDs, jet pumps constitute the primary dredging tool. Through a jet beam equipped with multiple nozzles, they inject large volumes of low-pressure water to disrupt sediment cohesion, create a fluidized layer, and rely on tidal or river currents to transport the re-suspended material.
- **Bow thrusters:** Bow thrusters, located at the bow, provide lateral thrust to enhance maneuverability and enable precise positioning. In TSHDs, they are particularly useful in confined environments, such as ports or narrow channels, where accurate alignment is required to maintain the dredging track. They support fine movements and vessel stability. WIDs use bow thrusters similarly to maintain the correct orientation relative to water flow, optimizing jet pump performance and counteracting external forces such as wind and currents.
- **Board net:** The board net, or onboard electrical distribution system, supplies power to operational equipment and crew facilities. In TSHDs, it feeds auxiliary systems such as hydraulics, winches, lighting, and general services. For WIDs, the board net ensures stable power delivery to dredging components, with real-time monitoring enabling dynamic adjustments that improve jet pump efficiency and overall operational performance.

The active energy consumers for each operational stage of TSHDs and WIDs are identified to determine stage-specific power consumption (see Table A.1).

Table A.1.: Active energy consumers per dredging stage for both TSHD and WID vessels.

Energy consumer	TSHD				WID		
	Sailing empty	Loading	Sailing full	Unloading	Dredging	Sailing	Prepare
Propulsion	✓	✓	✓	✓	✓	✓	
Dredge pumps		✓					
Jet pumps		✓		✓	✓		
Bow thrusters		✓		✓	✓		
Board net	✓	✓	✓	✓	✓	✓	✓

A.1. PROPULSION POWER

Propellers supply the maneuverability and thrust needed for sailing, dredging, and transporting sediment. In a TSHD, diesel engines serve as the primary power source for these activities, whereas a WID additionally makes use of natural seabed currents and tidal flows to support sediment re-mobilization. The propulsion power $P_{propulsion}$ for each activity is determined by the total resistance R_{total} acting on the vessel, the vessel speed v required to overcome this resistance, and the overall efficiency η_{total} associated with that operational condition.

$$P_{propulsion} = \frac{v \times R_{total}}{\eta_{total}} \quad (A.1)$$

The total resistance R_{total} is determined by summing the major resistance components acting on the vessel: frictional resistance R_F , appendage resistance R_{APP} , wave resistance R_W , bulbous-bow resistance R_B , immersed-transom resistance R_{TR} , and residual resistance R_A . During dredging operations, vessels experience an additional resistance component caused by dredging appendages (Holtrop and Mennen, 1982; Janssen, 2023; Lamers, 2022; Prins, 2024; ter Meulen, 2018). The total efficiency η_{total} is defined as the product of several subsystem efficiencies, including open-water, hull, shaft, and gearing efficiencies, which vary depending on the specific activity performed by the vessel (Triantafyllou and Hover, 2003).

$$R_{total} = R_F(1 + k_1) + R_{APP} + R_W + R_B + R_{TR} + R_A \quad (A.2)$$

During sailing stages, the vessel is subjected to several types of resistance, including frictional, wave, pressure, and residual components. The overall resistance is obtained by summing these contributions (see Equation A.2). Table ?? provides an overview of the parameters and terminology used to compute the total resistance during sailing.

A.1.1. RESISTANCE DUE TO FRICTION

Frictional resistance arises from skin friction, viscous effects, and the influence of appendages acting on the vessel during sailing. The total frictional resistance is calculated as follows.

$$R_{Friction} = R_F(1 + k_1) + R_{APP} \quad (A.3)$$

FRICTIONAL RESISTANCE

The frictional resistance (R_F) is calculated using a function of the Reynolds number ($Re = \frac{V \times L_{wl}}{n_u}$) (Roh *et al.*, 2018).

$$R_F = \frac{1}{2} \times \rho \times C_{F0} \times S_T \times V^2 \quad (A.4)$$

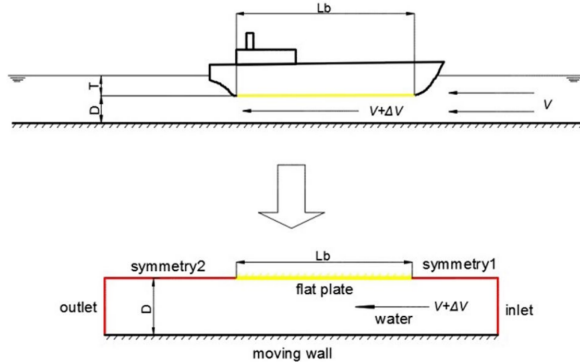
The value for the frictional resistance coefficient (C_{F0}) is calculated as follows (ITTC, 2002).

$$C_{F0} = \frac{0.075}{(\log Re - 2)^2} = \frac{0.075}{(\log \frac{V \times L_a}{v} - 2)^2} \quad (A.5)$$

A correction factor is applied to Equation A.5 to account for shallow-water effects, incorporating vessel dimensions and draught (Zeng *et al.*, 2019). A simplified representation of the vessel bottom under shallow-water conditions is shown in Figure A.1.

Table A.2.: Notations of resistance terms during sailing.

Notation	Description
C_{F0}	Frictional resistance coefficient [-]
C_M	Midship section coefficient [-]
C_B	Block coefficient [-]
C_{WP}	Water plane area coefficient [-]
C_P	Prismatic coefficient [-]
C_A	Residual resistance coefficient [-]
C_{deep}	Deep friction coefficient [-]
$C_{shallow}$	Shallow friction coefficient [-]
C_{katsui}	Katsui friction coefficient [-]
C_{stern}	Stern coefficient [-]
C_{lA}	Coefficient based on the specific shape of the afterbody and C_{stern} ($=1$) [-]
A_T	Transverse sectional area of the transom at zero speed [-]
A_{BT}	Transverse sectional area of the bulbous bow [-]
h_B	Position of the center of the transverse area of the bulbous bow [-]
S_B	Wetted surface of the flat bottom of a vessel [m^2]
S_T	Wetted surface of a vessel [m^2]
V	Vessel speed [m/s]
V_B	Vessel speed considering shallow-water effect [m/s]
$V + \Delta V$	Accelerated vessel speed [m/s]
T	Vessel draught [m]
T_F	Vessel forward draught [m]
B	Vessel width [m]
L_a	Length of the vessel at the waterline [m]
L_b	Length of the flat at the bottom [m]
L_{wl}	Length of flat plane at the water level [m]
L_r	Length of run [m]
ν	Kinematic viscosity [m^2/s]
d	Distance between the sample point and the flat plate [m]
D	Under-keel clearance [m]
Δ	Displacement of water [m^3]
ρ	Density of seawater [kg/m^3]
n_u	Water viscosity [-]
i_E	Angle of the waterline at the bulbous bow [degrees]

Figure A.1.: Simplification of vessel bottom in shallow water (Zeng *et al.*, 2019).

The proposed C_{F0} cannot be applied directly, as vessels also have non-horizontal wet surfaces that must be considered. Consequently, the frictional coefficient is calculated separately for shallow- and deep-water conditions as follows.

$$C_f = \begin{cases} C_{F0} + (C_{deep} - C_{katsui}) \times \frac{S_B}{S_T} & \frac{(d-T)}{L_{wl}} > 1 \\ C_{F0} + (C_{shallow} - C_{katsui}) \times \frac{S_B}{S_T} \times \left(\frac{V_B}{V}\right)^2 & \frac{(d-T)}{L_{wl}} \leq 1 \end{cases} \quad (A.6)$$

The Katsui (C_{katsui}), deep (C_{deep}), and shallow ($C_{shallow}$) friction coefficients are calculated as follows.

$$C_{katsui} = \frac{0.0066577}{(\log Re - 4.3762)^a} \quad (A.7)$$

$$C_{deep} = \frac{0.08169}{(\log Re - 1.717)^2} \quad (A.8)$$

$$C_{shallow} = \frac{0.08169}{(\log Re - 1.717)^2} \times \left(1 + \left(\frac{0.003998}{(\log Re - 4.393) \times \left(\frac{d-T}{L_{wl}}\right)^{-1.083}}\right)\right) \quad (A.9)$$

Where $a = 0.042612 \times \log Re + 0.26725$ and the vessel's speed under shallow water effect is taken into account when $\frac{d}{T} \leq 4$ and calculated as follows.

$$V_B = 0.4277 \times V \times e^{\left(\frac{d}{T}\right)^{-0.07625}} \quad (A.10)$$

For the rest of the cases, it is considered that $V_B = V$. The wetted surface area of the vessel (S_T) is calculated as follows (Holtrop and Mennen, 1982).

$$S_T = L_a(2T + B)\sqrt{C_M}(0.453 + 0.4425C_B - (0.2852C_M) - (0.003467\frac{B}{T}) + 0.2696C_{WP}) + 2.38\frac{A_{BT}}{C_B} \quad (A.11)$$

Where the block coefficient (C_B) of a vessel is the ratio of underwater volume of the vessel to the volume of a rectangular block having the same overall length and takes the value of 0.85 for dredging vessels (Vlasblom, 2007). The midship section coefficient (C_M) is the ratio between the area of the midship section under the water surface and a rectangle with the same depth and width. According to Bertram and Schneekluth (1998), C_M is dependent on the value of C_B shown in Figure A.2. The value of 0.85 for C_B results in $C_M = 1$.

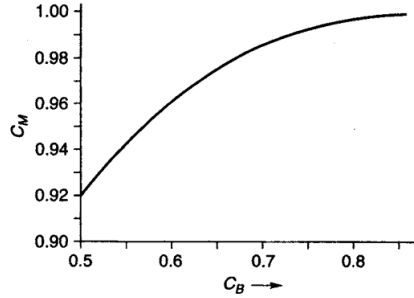


Figure A.2.: Midship coefficient and its relationship with block coefficient (Bertram and Schneekluth, 1998).

The water plan area coefficient (C_{WP}) is calculated as follows (Bertram and Schneekluth, 1998).

$$C_{WP} = \frac{(1 + 2C_B)}{3} \quad (A.12)$$

Additionally, the wet transverse sectional area of the bulbous bow (A_{BT}) helps in reducing the drag by inducing the flow around the hull, which is calculated as follows (Ventura, 2022).

$$A_{BT} = C_{BB} \times B \times T \times C_M \quad (A.13)$$

Where the typical value for C_{BB} is 0.2. Therefore, all terms included in the calculation of the frictional resistance are determined.

VISCOUS RESISTANCE

The form factor $(1 + k_1)$ describes the viscous resistance of the hull about the frictional resistance. The value of the form factor is shown as follows (Roh *et al.*, 2018).

$$1 + k_1 = 0.93 + 0.487118 \times C_{14} \left(\frac{B}{L_a}\right)^{1.06806} \times \left(\frac{T}{L_a}\right)^{0.46106} \times \left(\frac{L_a}{L_r}\right)^{0.121563} \times \left(\frac{L_a^3}{\Delta}\right)^{0.36486} \times (1 - C_P)^{-0.60247} \quad (\text{A.14})$$

The volume of displaced water is calculated as follows (Holtrop and Mennen, 1982).

$$\Delta = C_B \times B \times T \times L_a \quad (\text{A.15})$$

The prismatic coefficient (C_P) is calculated as a ratio of the displacement volume to the volume of a prism that has a length (between the perpendicular and cross-sectional area equal to C_M (Rawson and Tupper, 2001). Therefore, C_P is calculated as follows (Holtrop and Mennen, 1982).

$$C_P = \frac{C_B}{C_M} \quad (\text{A.16})$$

The stern coefficient (C_{stern}) in the context of viscous resistance in a ship is a parameter that quantifies the effect of the ship's stern shape on its total viscous resistance. It is used in empirical and semi-empirical methods for estimating resistance. The stern region of a ship influences the development of the boundary layer and wake flow, which in turn affects the viscous resistance. According to vessel characteristics, C_{14} is calculated based on the C_{stern} and takes the value of 1 for this case study. The length of run (L_r) in ship hydrodynamics refers to the distance from the forward stagnation point (often near the bow) to the stern, specifically following the path of the flow along the ship's hull (Roh *et al.*, 2018).

$$\frac{L_r}{L_a} = 1 - C_P + \frac{0.06C_P \times l_{cb}}{4C_P - 1} \quad (\text{A.17})$$

The value for l_{cb} refers to the longitudinal position of the center of buoyancy (either forward (+) or afterword (-)), can be described as follows (Segers, 2021).

$$l_{cb} = -13.5 + 19.4C_P \quad (\text{A.18})$$

Therefore, all terms included in the calculation of the viscous resistance are determined.

APPENDAGE RESISTANCE

The appendage resistance (R_{APP}) is a frictional resistance factor, that usually is considered small (in the order of 10 times smaller than the frictional resistance calculated as follows (Rawson and Tupper, 2001; Roh *et al.*, 2018).

$$R_{APP} = \frac{1}{2} \times \rho \times C_{F0} \times S_{APP} \times V^2 \times (1 + k_2) \quad (\text{A.19})$$

Where k_2 depends on the combination of appendages that is different for each vessel. The term $(1 + k_2)$ is calculated as follows.

$$1 + k_2 = \sum \frac{S_{APP} \times (1 + k_2)}{\sum S_{APP}} \quad (\text{A.20})$$

Due to simplicity, a value of 2.5 is considered for k_2 (Segers, 2021). The value for S_{APP} is estimated to be approximately 10% of the total wetted area (S_T) (Rawson and Tupper, 2001).

A.1.2. WAVE RESISTANCE

The wave resistance (R_W) depends on the hull's size and shape and the vessel's sailing speed. When sailing, the vessel creates waves in the surrounding area of the hull that pose resistance to the vessel (Segers, 2021). Froude number (F_n) is a dimensionless number used in naval architecture and fluid dynamics to compare the inertial and gravitational forces acting on a vessel as it moves through water. It helps determine the vessel's resistance, wave-making characteristics, and planing behavior (Wu *et al.*, 2019).

$$F_n = \frac{V}{\sqrt{g \times L_{wl}}} \quad (\text{A.21})$$

According to the obtained F_n , the wave resistance (R_W) is calculated as follows.

$$R_W = c_1 \times c_2 \times c_5 \times \nabla \times \rho \times g \times \exp(m_1 \times F_n^{-0.9} + m_2 \times \cos(\lambda \times F_n^{-2})) \quad (\text{A.22})$$

Different coefficients used in Equation A.22 are obtained as follows.

$$c_1 = 0.2223105 \times c_7^{3.78613} \times \left(\frac{T}{B}\right)^{1.07961} \times (90 - i_E)^{-1.37165} \quad (\text{A.23})$$

$$c_2 = \exp(-1.89 \times \sqrt{c_3}) \quad (\text{A.24})$$

$$c_3 = \frac{(0.56 \times A_{BT}^{1.5})}{(B \times T \times (0.31 \times \sqrt{A_B \times T} + T_F - h_B))} \quad (\text{A.25})$$

$$c_5 = 1 - \frac{(0.8 \times A_T)}{(B \times T \times C_M)} \quad (\text{A.26})$$

$$c_7 = \begin{cases} 0.229577 \times \left(\frac{B}{L_{wl}}\right)^{0.33333} & \frac{B}{L_{wl}} < 0.11 \\ 0.5 - 0.0625 \times \left(\frac{B}{L_{wl}}\right) & \frac{B}{L_{wl}} > 0.25 \\ \left(\frac{B}{L_{wl}}\right) & 0.11 < \frac{B}{L_{wl}} < 0.25 \end{cases} \quad (\text{A.27})$$

$$c_{15} = \begin{cases} -1.69385 & \frac{L^3}{\nabla} < 512 \\ 0 & \frac{L^3}{\nabla} > 1727 \\ -1.69385 + \frac{(\frac{L}{\nabla^{1/3}} - 8)}{2.36} & 512 < \frac{L^3}{\nabla} < 1727 \end{cases} \quad (\text{A.28})$$

$$c_{16} = \begin{cases} 8.07981 \times C_P - 13.8673 \times C_P^2 + 6.984388 \times C_P^3 & C_P < 0.8 \\ 1.73014 - 0.7067 \times C_P & C_P < 0.8 \end{cases} \quad (\text{A.29})$$

Where c_2 accounts for the reduction of wave resistance due to the action of the bulbous bow, c_3 determines the influence of the bulbous bow on the wave resistance, and c_5 expresses the influence of a transom stern on the wave resistance (Holtrop and Mennen, 1982). Other parameters are calculated as follows.

$$\lambda = \begin{cases} 1.446 \times C_P - 0.03 \times \left(\frac{L}{B}\right) & \frac{L}{B} < 12 \\ 1.446 \times C_P - 0.36 & \frac{L}{B} > 12 \end{cases} \quad (\text{A.30})$$

$$m_1 = 0.0140407 \times \frac{L}{T} - 1.75254 \times \frac{\nabla^{1/3}}{L} - 4.79323 \times \frac{B}{L} - c_{16} \quad (\text{A.31})$$

$$m_2 = c_{15} \times C_P^2 \times \exp(-0.1 \times F_n^2) \quad (\text{A.32})$$

The half angle of the entrance (i_E) is the angle of the waterline at the bulbous bow in degrees concerning the center place and neglecting the local shape of the stem.

$$i_E = 1 + 89 \times \exp\left(-\left(\frac{L_{wl}}{B}\right)^{0.80856} \times (1 - C_{WP})^{0.30484} \times (1 - C_P - 0.0225 \times lcb)^{0.6367} \times \left(\frac{L_r}{B}\right)^{0.34574} \times \left(100 \times \frac{\nabla}{L_{wl}^3}\right)^{0.16302}\right) \quad (\text{A.33})$$

Equation A.33 is obtained by regression analysis of over 200 hull shapes, yields i_E value for exceptional combinations of hull-form parameters (Holtrop and Mennen, 1982).

A.1.3. PRESSURE RESISTANCE

The total resistance due to pressure that is experienced by the vessel consists of the resistance due to the bulbous bow and immersed transom stern.

$$R_{Pressure} = R_B + R_{TR} \quad (A.34)$$

RESISTANCE DUE TO BULBOUS BOW

A bulbous bow is a protruding, bulb-like structure at the front (bow) of a vessel, just below the waterline. It is designed to reduce wave resistance and improve the vessel's fuel efficiency and stability. As a vessel moves, it creates bow waves that increase resistance. The bulbous bow generates its wave system, which interacts with the vessel's bow waves. If designed correctly, these two wave systems partially cancel each other out, reducing overall wave-making resistance. The total resistance due to a bulbous bow (R_B) is dependent on the shape of the bow calculated as follows (Roh *et al.*, 2018).

$$R_B = \frac{0.11 \times \exp(-3 \times P_B^{-2}) \times F_{ni}^3 \times A_{BT}^{1.5} \times \rho \times g}{1 + F_{ni}^2} \quad (A.35)$$

Where the values for the coefficient for the emergence of the bulbous bow (P_B) and the Froude number based on the immersion of the bulbous bow (F_{ni}) are calculated as follows.

$$P_B = \frac{0.56 \times \sqrt{A_{BT}}}{T_F - 1.5 \times h_B} \quad (A.36)$$

$$F_{ni} = \frac{V}{\sqrt{g \times (T_F - h_B - 0.25 \times \sqrt{A_{BT}} + 0.15 \times V^2)}} \quad (A.37)$$

RESISTANCE DUE TO IMMERSED TRANSON

An immersed transom stern refers to a ship's flat or nearly flat stern that is partially or fully submerged below the waterline. This design affects the vessel's hydrodynamics, particularly wave resistance and wake formation. Unlike a traditional pointed or rounded stern, an immersed transom is a vertical or slightly sloped flat surface that extends below the water. Therefore, a larger hull area is in contact with water, which can affect the drag. Moreover, the interaction between the water flowing past the hull and the transom creates turbulence and waves, impacting efficiency. The resistance that is built up due to the immersed transom is created the same way as the bulbous bow due to their identical shape (Roh *et al.*, 2018). Resistance due to immersed transom is calculated as follows.

$$R_{TR} = \frac{1}{2} \times \rho \times c_6 \times A_T \times V^2 \quad (A.38)$$

The immersed area of transom (A_T) is calculated as follows (Segers, 2021).

$$A_T = 0.2 \times B \times T \quad (A.39)$$

Subsequently, the value for c_6 is determined by the Froude number (F_{nT}) that is based on the immersion of the transom. The Froude number is calculated as follows.

$$F_{nT} = \frac{V}{\sqrt{\frac{2 \times g \times A_T}{B + B \times C_{WP}}}} \quad (A.40)$$

$$c_6 = \begin{cases} 0 & F_{nT} \geq 5 \\ 0.2 \times (1 - 0.2 \times F_{nT}) & F_{nT} < 5 \end{cases} \quad (A.41)$$

A.1.4. RESIDUAL RESISTANCE

The model-ship correlation resistance (R_A) is a part of the residual resistance. R_A (also called wave-making resistance) is the portion of a ship's total resistance that remains after accounting for viscous resistance (friction and pressure drag). It primarily comes from wave generation and eddies as the ship moves through the water and explains the difference between estimated and actual values for total resistance (Roh *et al.*, 2018).

$$R_A = \frac{1}{2} \times \rho \times C_A \times S_T \times V^2 \quad (\text{A.42})$$

Where the residual resistance coefficient (C_A) is calculated as follows.

$$C_A = 0.006 \times (L_{wl} + 100)^{-0.16} - 0.00205 + 0.003 \times \sqrt{\frac{L_{wl}}{7.5}} \times C_B^4 \times C_2 \times (0.04 - C_4) \quad (\text{A.43})$$

Where $C_4 = \frac{T_F}{L_{wl}}$ with a maximum value of 0.04.

A.1.5. KARPOV CALCULATIONS

After analyzing all resistance terms of the vessel using the method proposed by Holtrop and Mennen (1982), some extra modifications can help in enhancing the vessel's speed according to the Froude number. A correction factor (α_{xx}) is used to update the vessel's sailing speed compared to the initial speed. In this regard, the Froude number is calculated based on the initial vessel's speed as follows.

$$F_n = \frac{V_0}{\sqrt{g \times h}} \quad (\text{A.44})$$

Thereafter, different values are studied based on the relationship between water depth and the vessel's draught. The modified vessel's speed (V_2) is calculated as follows.

$$V_2 = \frac{V_0}{\alpha_{xx}} \quad (\text{A.45})$$

The modified vessel's speed is used for the calculations of the total resistance as it results in a higher power profile compared to the original approach proposed by Holtrop and Mennen (1982). The value obtained for V_2 is used to calculate the wave and residual resistance and V_0 is adopted to calculate the resistance due to frictions. The following calculations are used to determine the value for α_{xx} .

if $F_{nh} \leq 0.4$:

$$\alpha_{xx} = \begin{cases} (-410^{-12})F_{nh}^3 - 0.2143F_{nh}^2 - 0.0643F_{nh} + 0.9997 & (0 \leq \frac{h}{T} < 1.75) \\ -0.8333F_{nh}^3 + 0.25F_{nh}^2 - 0.0167F_{nh} + 1 & (1.75 \leq \frac{h}{T} < 2.25) \\ -1.25F_{nh}^4 + 0.5833F_{nh}^3 - 0.0375F_{nh}^2 - 0.0108F_{nh} + 1 & (2.25 \leq \frac{h}{T} < 2.75) \\ 1 & (\frac{h}{T} \geq 2.75) \end{cases} \quad (\text{A.46})$$

if $F_{nh} > 0.4$:

$$\alpha_{xx} = \begin{cases} -0.9274F_{nh}^6 + 9.5953F_{nh}^5 - 37.197F_{nh}^4 + 69.666F_{nh}^3 - 65.391F_{nh}^2 + 28.025F_{nh} - 3.4143 & (0 \leq \frac{h}{T} < 1.75) \\ 2.2152F_{nh}^6 - 11.852F_{nh}^5 + 21.499F_{nh}^4 - 12.174F_{nh}^3 - 4.7873F_{nh}^2 + 5.8662F_{nh} - 0.2652 & (1.75 \leq \frac{h}{T} < 2.25) \\ 1.2205F_{nh}^6 - 5.4999F_{nh}^5 + 5.7966F_{nh}^4 + 6.6491F_{nh}^3 - 16.123F_{nh}^2 + 9.2016F_{nh} - 0.6342 & (2.25 \leq \frac{h}{T} < 2.75) \\ -0.4085F_{nh}^6 + 4.534F_{nh}^5 - 18.443F_{nh}^4 + 35.744F_{nh}^3 - 34.381F_{nh}^2 + 15.042F_{nh} - 1.3807 & (2.75 \leq \frac{h}{T} < 3.25) \\ 0.4078F_{nh}^6 - 0.919F_{nh}^5 - 3.8292F_{nh}^4 + 15.738F_{nh}^3 - 19.766F_{nh}^2 + 9.7466F_{nh} - 0.6409 & (3.25 \leq \frac{h}{T} < 3.75) \\ 0.3067F_{nh}^6 - 0.3404F_{nh}^5 - 5.0511F_{nh}^4 + 16.892F_{nh}^3 - 20.265F_{nh}^2 + 9.9002F_{nh} - 0.6712 & (3.75 \leq \frac{h}{T} < 4.5) \\ 0.3212F_{nh}^6 - 0.3559F_{nh}^5 - 5.1056F_{nh}^4 + 16.926F_{nh}^3 - 20.253F_{nh}^2 + 10.013F_{nh} - 0.7196 & (4.5 \leq \frac{h}{T} < 5.5) \\ 0.9252F_{nh}^6 - 4.2574F_{nh}^5 + 5.0363F_{nh}^4 + 3.3282F_{nh}^3 - 10.367F_{nh}^2 + 6.3993F_{nh} - 0.2074 & (5.5 \leq \frac{h}{T} < 6.5) \\ 0.8442F_{nh}^6 - 4.0261F_{nh}^5 + 5.313F_{nh}^4 + 1.6442F_{nh}^3 - 8.1848F_{nh}^2 + 5.3209F_{nh} - 0.0267 & (6.5 \leq \frac{h}{T} < 7.5) \\ 0.1211F_{nh}^6 + 0.628F_{nh}^5 - 6.5106F_{nh}^4 + 16.7F_{nh}^3 - 18.267F_{nh}^2 + 8.7077F_{nh} - 0.4745 & (7.5 \leq \frac{h}{T} < 8.5) \\ \begin{cases} 1 & (F_{nh} < 0.6) \\ -6.4069F_{nh}^6 + 47.308F_{nh}^5 - 141.93F_{nh}^4 + 220.23F_{nh}^3 - 185.05F_{nh}^2 + 79.25F_{nh} - 12.484 & (F_{nh} \geq 0.6) \end{cases} & (8.5 \leq \frac{h}{T} < 9.5) \\ \begin{cases} 1 & (F_{nh} < 0.6) \\ -6.0727F_{nh}h^6 + 44.97F_{nh}h^5 - 135.21F_{nh}h^4 + 210.13F_{nh}h^3 - 176.72F_{nh}h^2 + 75.728F_{nh}h - 11.893 & (F_{nh} \geq 0.6) \end{cases} & (\frac{h}{T} \geq 9.5) \end{cases} \quad (A.47)$$

The resistance terms of the TSHD during the trailing stage are presented in ter Meulen (2018) by analyzing the forces posed to the draghead and the suction pipe of the vessel.

A.2. PUMP POWER

The working point of a pump is defined as the operating condition where the pump's flow rate Q and head H satisfy the requirements of the system, determined by the pipeline resistance. This point corresponds to the intersection of the pump curve and the pipeline resistance curve. The flow rate Q [in m^3/s] indicates the volume of fluid the pump moves per unit time, while the head H [in m] represents the height to which the pump can lift or pressurize the fluid. At the working point, the pump and pipeline system are in equilibrium: the pump generates sufficient head to overcome the system resistance, and the flow rate reflects the volume of fluid the pump can deliver under that head (Brown, 2002).

The pump working point is determined by the interaction between the pump and the pipeline system, represented by two curves:

- **System curve:** Shows the relationship between the head (pressure) required by the system and the flow rate. It is derived from the head loss equations (e.g., Darcy–Weisbach for water or mixture flows). As flow rate increases, head loss rises, causing the system curve to slope upward.
- **Pump curve:** Illustrates the pump's capability to generate head at varying flow rates. Provided by the pump manufacturer, it indicates the head that the pump can deliver for each flow rate.

The pump working point for the TSHD used in this study is shown in Figure A.3.

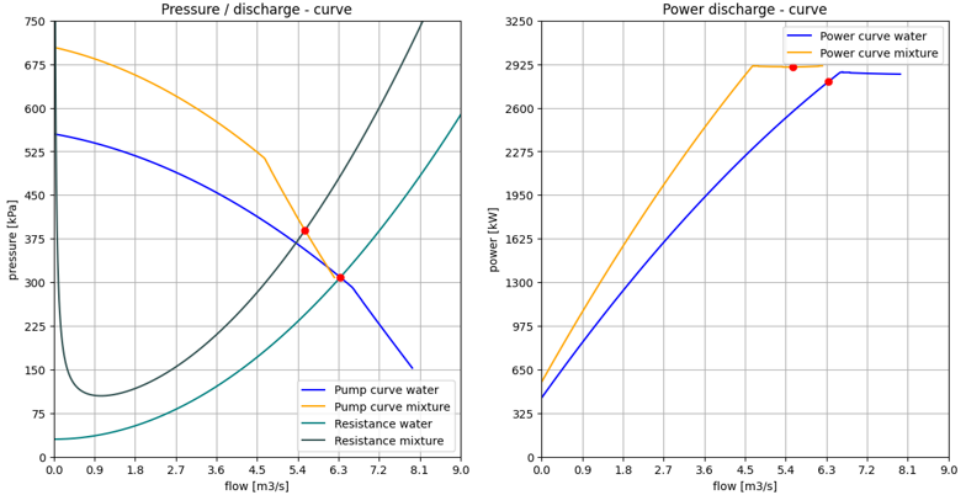


Figure A.3.: Visualizing system curve and pump curve (left) for the TSHD including the working point (red point) and pump power curve in the working point (right) (Janssen, 2023).

To determine the pump working point, the pipeline resistance (head loss) must be evaluated separately for water flow and for mixture flow. The notations listed in Table A.3 are used to formulate the pipeline resistance model.

The total head loss in the system, resulting from pipeline resistance and other factors, is a key component of the system curve. Head loss depends on the flow rate, pipe characteristics, and fluid properties, and typically increases with the square of the flow rate under turbulent conditions. Consequently, higher flow rates require the pump to overcome greater resistance. For a given flow rate, head loss can be calculated using the Darcy–Weisbach equation or its variants, allowing the system curve to be plotted.

The pump working point is defined by the intersection of the pump curve and the system curve. At this point, the flow rate corresponds to the volume the pump delivers against the system's resistance, and the head represents the pressure generated to overcome the total system resistance, including pipeline losses. This intersection establishes the pump's operating conditions, including flow rate, head, and power requirements (see Figure A.3). The pump power at the working point is directly related to both the flow rate and the head, and is calculated as follows:

$$P_{pump} = \frac{\rho \times g \times Q \times H_{total}}{\eta_{pump}} \quad (\text{A.48})$$

If the head loss increases due to changes in pipeline resistance, such as modifications to the pipeline design or variations in the properties of the pumped mixture, a different pump may need to be selected, or the operating conditions (e.g., speed, impeller diameter) adjusted to achieve the required flow rate and head (Valiantzas, 2008).

A.2.1. PUMP HEAD FOR WATER FLOW

The actual friction factor (λ) is calculated based on the model number for pipe friction calculations (λ_{model}). This calculation is done based on empirical models.

$$\lambda = \begin{cases} 0.0388 \times (d_{pipe} \times 1000)^{-0.1894} & \lambda_{model} = 1 \\ 0.0137 \times \left(\frac{4 \times Q}{\pi \times d_{pipe}^2} \right) \times d_{pipe}^{-0.25} & \lambda_{model} = 2 \end{cases} \quad (\text{A.49})$$

The total pump head required to overcome pipeline resistance for water flow is calculated by summing the following components:

Table A.3.: Parameters for the pumps.

Notation	Description
Q	Volumetric flow rate of water [m^3/s]
d_{pipe}	Pipeline diameter [m]
l_{pipe}	Pipeline length [m]
sg_{water}	Water specific gravity [kg/m^3]
sg_{grain}	Grain specific gravity [kg/m^3]
sg_{lump}	Lump specific gravity [kg/m^3]
g	Gravitational acceleration [m/s^2]
h_{pump}	Pump head contribution [-]
λ_{model}	Model number for pipe friction calculation [-]
λ	Friction factor [-]
$\xi_{additional}$	Additional head loss coefficient [-]
$h_{reclamation}$	Height of material discharge above the water surface [m]
h_{pump}	Pump head added by the dredge pump [m]
dmf	Particle size [μm]
H_{total}	Pump total head [kPa]
η_{pump}	Pump efficiency [-]

- **Static head:** The vertical height difference between the liquid levels at the source and destination. It includes the suction static head (from the liquid level in the suction tank to the pump centerline) and the discharge static head (from the pump centerline to the liquid level in the discharge tank).
- **Vacuum head:** The negative pressure at the pump suction side, typically expressed as a liquid column height. It arises when the pump lifts fluid from a source below its inlet, requiring it to overcome atmospheric pressure. Excessive suction lift can lead to cavitation.
- **Additional head:** Extra head required due to system-specific needs, such as discharge pressure requirements, acceleration forces, or varying operational conditions.
- **Head loss:** Energy lost due to friction and turbulence as the fluid flows through pipes, fittings, valves, and other system components. This includes frictional losses from pipe-wall interactions and minor losses from bends, valves, and other obstructions. Head loss reduces the effective energy delivered by the pump and must be incorporated in system design.

$$H_{total.water} = H_{pipeline.water} + H_{additional} + H_{vacuum} + H_{static} \quad (A.50)$$

Head loss terms are calculated using the Darcy-Weisbach equation as follows (Brown, 2002).

$$H_{pipeline.water} = \lambda \times \left(\frac{l_{pipe}}{d_{pipe}} \right) \times 0.5 \times sg_{water} \times v^2 \quad (A.51)$$

where v is the flow velocity calculated by dividing the flow rate (Q) by the pipeline area as $v = \frac{4 \times Q}{\pi \times d_{pipe}^2}$

$$H_{additional} = \xi_{additional} \times 0.5 \times sg_{water} \times v^2 \quad (A.52)$$

$$H_{static} = (h_{reclamation} + h_{pump}) \times g \times sg_{water} \quad (A.53)$$

$$H_{vacuum} = ((Z - h_{pump}) \times g + \xi_{water} \times 0.5 \times v^2) \times sg_{water} - Z \times g \times sg_{water} \quad (A.54)$$

A.2.2. PUMP HEAD FOR MIXTURE FLOW

The pipeline resistance for mixture flow is calculated for dredge pumps of a TSHDs. The actual friction factor (λ) is calculated similarly to the case of water flow (Equation A.49). The only difference is that additional head loss terms affect the total head loss, which are elaborated using the Darcy-Weisbach equation as follows (Brown, 2002).

$$H_{\text{pipeline.mixture}} = \begin{cases} H_{\text{pipeline.water}} & dm f < 60\mu m \\ H_{\text{pipeline.water}} + \frac{sg_{\text{mix}} - sg_{\text{water}}}{sg_{\text{grain}} - sg_{\text{water}}} & 60 \leq dm f < 2200 \\ \times l_{\text{pipeline}} \times g \times sg_{\text{water}} \times \frac{skt}{v} & \\ H_{\text{pipeline.water}} + \left(\frac{sg_{\text{mix}} - sg_{\text{water}}}{sg_{\text{grain}} - sg_{\text{water}}} \right)^{3/2} & \\ \times 2.1 \times \frac{1}{v} \times \left(\frac{sg_{\text{mix}} - sg_{\text{water}}}{sg_{\text{grain}} - sg_{\text{water}}} \right) \times l_{\text{pipe}} \times g \times sg_{\text{water}} & dm f \geq 2200 \end{cases} \quad (\text{A.55})$$

where $skt = 0.0000001 \times dm f^2 + 0.0014 \times dm f - 0.1365$.

$$H_{\text{additional}} = \xi_{\text{additional}} \times 0.5 \times sg_{\text{mixture}} \times v^2 \quad (\text{A.56})$$

$$H_{\text{static}} = (h_{\text{reclamation}} + h_{\text{pump}}) \times g \times sg_{\text{mixture}} \quad (\text{A.57})$$

$$H_{\text{vacuum}} = ((Z - h_{\text{pump}}) \times g + \xi_{\text{water}} \times 0.5 \times v^2) \times sg_{\text{mixture}} - Z \times g \times sg_{\text{water}} \quad (\text{A.58})$$

Having all head loss terms, the total head loss is calculated as follows.

$$H_{\text{total}} = H_{\text{pipeline.mixture}} + H_{\text{additional}} + H_{\text{vacuum}} + H_{\text{static}} \quad (\text{A.59})$$

Pump coefficients are calculated based on empirical data and pump characteristics.

B

APPENDIX B

This appendix details the methodology used to estimate the duration of individual dredging activities and the corresponding production rates, which form the foundation for calculating total energy consumption and emissions. Sailing duration for each activity is derived from the fundamental relationship between sailing distance d and vessel speed v , expressed as $t = \frac{d}{v}$. Assuming linear transit paths between two locations, the total sailing distance is approximated by summing the linear segments between multiple intermediate points, while adopting an average sailing speed representative of operational conditions. This simplification neglects hydrodynamic variability and maneuvering delays but provides a consistent baseline for comparative analysis.

The following sections outline the procedures used to estimate:

- Loading and unloading durations for a Trailing Suction Hopper Dredger (TSHD), based on hopper capacity, pump-out rates, and port handling constraints.
- Total dredging duration for a Water Injection Dredger (WID), derived from jetting system parameters, sediment loosening efficiency, and hydrodynamic transport assumptions.

Together, these procedures establish a coherent framework for linking operational activity durations to production rates, enabling subsequent calculation of energy demand and emissions across different dredging strategies.

B.1. TOTAL LOADING AND UNLOADING DURATION OF A TSHD

The total loading duration of a TSHD is computed based on the total hopper capacity of the vessel (V_{hopper} , in m^3) and its excavation production rate ($Q_{\text{excavation}}$, in m^3/s). Similarly, the unloading duration is determined by assuming a constant discharge rate ($C_{\text{unloading}}$) during bottom door operations:

$$t_{\text{loading.tshd}} = \frac{V_{\text{hopper}}}{Q_{\text{excavation.tshd}}} \quad (\text{B.1})$$

$$t_{\text{unloading.tshd}} = \frac{V_{\text{hopper}}}{C_{\text{unloading}}} \quad (\text{B.2})$$

B.1.1. TOTAL EXCAVATION PRODUCTION OF A TSHD

The total excavation production of a TSHD comprises three main components: jet production for sediment loosening (Van Rhee, 2017; Vlasbom, 2003), cut production for material cutting and suction into the hopper (de Jonge, 2017; ter Meulen, 2018), and erosion production. In this study, overflow is assumed to be prohibited. Each production term is influenced by factors such as sediment properties, penetration depth of cutting teeth and jet nozzles, and sediment mass flux. During the loading phase, sediments accumulate in the hopper until the mixture reaches a target density. In typical operations, overflow occurs when excess water is discharged to increase the density of the retained load before final discharge. This process can generate sediment plumes around the vessel, which may be restricted in environmentally sensitive areas.

Figure B.1 illustrates a typical dredging cycle for a TSHD. The total loading duration can be divided into two phases: a linear phase up to the onset of overflow, and a non-linear phase during overflow. Initially, the hopper is filled with a water-sediment mixture via the dredge pumps, allowing sediment to settle and form

denser layers. As filling continues, excess water rises to the top and is discharged, permitting additional dense material to be added and further increasing the overall load density.

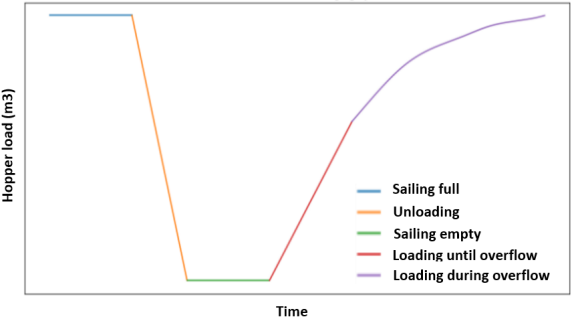


Figure B.1.: Schematic overview of a dredging cycle in TSHDs (Janssen, 2023).

In the Port of Ramsgate case study, overflow operations are restricted by local environmental regulations. As a result, the total loading duration is determined solely by the linear phase, during which sediments are loaded up to the point where overflow would otherwise occur. Consequently, the loading time depends on the hopper capacity and the suction production rate, which is the sum of excavation and vacuum production. Assuming sufficient vacuum power during suction, excavation production becomes the primary factor controlling the total production rate (Miedema, 2019).

Excavation production represents the volumetric rate at which material is effectively loosened, transported, and deposited into the hopper during the excavation phase. This rate is influenced by sediment properties, draghead performance, and suction pipe efficiency, and is modeled as the sum of jetting, cutting, and erosion components (Vlasbom, 2003):

$$Q_{excavation} = Q_{jetting} + Q_{cutting} + Q_{erosion} \tag{B.3}$$

The key parameters used in this formulation are summarized in Table B.1.

Table B.1.: Parameters for the production rate of a TSHD.

Notation	Description
ρ_{s0}	Sediment particle density [kg/m^3]
n_0	Initial porosity of sediment [-]
v_t	Trailing velocity [m/s]
n_n	Number of jet nozzles [-]
w	Visor width [m]
$Q_{jet,wp}$	Jet flow discharge at the working point [m^3/s]

CUT PRODUCTION

The cutting process performed by the draghead is thoroughly described by Miedema (2014), detailing the mechanics of sediment cutting across different soil types, including sand, clay, and rock. For sandy sediments, the saturated sand model is used, accounting for pore pressure effects to analyze stability, permeability, and shear resistance under varying loads.

In TSHD operations, the draghead employs flow cutting, wherein the draghead is dragged along the seabed to detach material (Figure B.2). The key parameters defining the process are the cutting velocity (v_c), blade angle (α), shear angle (β), and the horizontal (F_h) and vertical (F_v) forces acting on the blade. A is the blade tip, B is the end of the shear plane, C is the blade top, h_b is the blade height, h_i is the thickness of the layer cut.

Cutting teeth or rippers installed on the draghead mechanically fragment compacted soils, making them easier to suction. The cutting production rate is primarily governed by the trailing velocity, sediment type, draghead geometry, and cutting layer thickness ($h_{i,cut}$) (de Jonge, 2017).

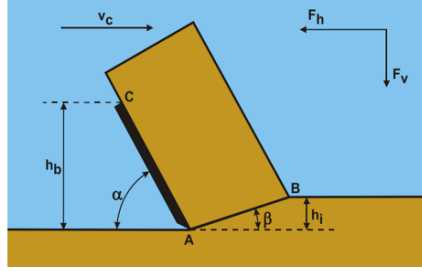


Figure B.2.: The flow type of cutting saturated sand (Miedema, 2014).

$$Q_{cut} = w \times h_{i,cut} \times v_t \quad (B.4)$$

The thickness of the cutting layer depends on both sediment characteristics and visor geometry (e.g., angle and length).

JET PRODUCTION

Jetting uses high-pressure water jets to loosen sediment and support suction. The process is influenced by key parameters such as sediment thickness, jet penetration depth ($h_{i,jet}$), and trailing velocity (v_t). As trailing velocity increases, the penetration depth generally decreases (Figure B.3).

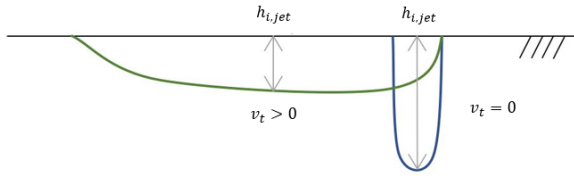


Figure B.3.: Impact of trailing speed on jet penetration depth (adopted from Janssen, 2023) (based on modified concepts presented in Miedema *et al.*, 2007; Van Rhee, 2017).

During operation, the draghead visor interacts with three distinct layers: jet, sled, and cutting, each exhibiting different mechanical and hydraulic behaviors. These layers are illustrated in Figures B.4–B.6, and their penetration depths are quantified using relationships based on visor geometry, length, and angle (γ). The penetration dynamics are described by a set of equations linking the total, sled, and cutting depths to the jet penetration depth. These cumulative relationships capture how the cutting and fluidization processes interact at different trailing velocities.

- **Jet layer:** The uppermost zone, where high-pressure water jets from the visor impact the seabed, fluidize and loosen the sediment, reducing its shear strength and facilitating transport. This process improves sediment removability by disrupting cohesion. The jet penetration depth is influenced by multiple factors and is expressed in Equation B.8. Assuming a constant visor angle γ at the onset of trailing, the jet penetration depth $h_{i,jet}$ initially exceeds the total affected layer thickness $h_{i,total}$, i.e., $h_{i,jet} > h_{i,total}$. Some of the jet water is lost beneath the visor, which continues descending until it encounters a solid layer. As trailing progresses, the jet layer eventually aligns with the total sediment thickness, and further increases in $h_{i,total}$ no longer affect visor forces ($h_{i,jet} = h_{i,total}$).
- **Sled layer:** As trailing speed increases, the visor penetration depth decreases ($h_{i,jet} < h_{i,total}$), bringing the visor into direct contact with a solid layer. In this phase, the visor acts as a sled moving over the seabed, forming the sled (or transport) layer beneath the jet layer. This layer consists of a mixture of loosened sediment and water, which is transported forward by the drag forces of the visor and the dredger (see Figure B.5). The jet stream continues to flow beneath the cutting teeth, preventing direct

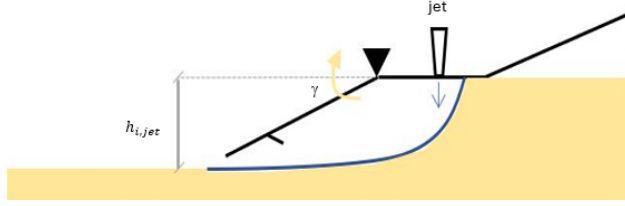


Figure B.4.: Jet layer thickness at the onset of trailing at low velocity (adopted from Janssen, 2023) (based on modified concepts presented in Miedema *et al.*, 2007; Van Rhee, 2017).

contact with the sediment ($h_{i,jet} > h_{i,total} - h_{i,sled}$). The sled penetration depth is influenced by the lengths of the visor and cutting teeth and increases gradually with trailing speed, calculated as:

$$h_{i,sled} = l_{visor} - l_{cut} \times \sin(\gamma) \quad (B.5)$$

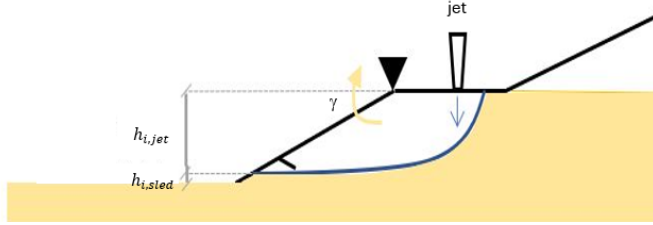


Figure B.5.: Sled layer thickness during trailing at higher velocities (adopted from Janssen, 2023) (based on modified concepts presented in Miedema *et al.*, 2007; Van Rhee, 2017).

- **Cutting layer:** At higher trailing velocities and reduced penetration depths, the cutting teeth engage the sediment bed ($h_{i,jet} < h_{i,total} - h_{i,sled}$). The cutting layer, or shear zone, forms the bottommost zone where mechanical interaction occurs. The visor applies cutting forces that shear the sediment into smaller fragments, which then enter the sled layer and are eventually transported into the suction pipe (see Figure B.6). The cutting penetration depth, which depends on the residual thickness of the upper layers, is calculated as:

$$h_{i,cut} = h_{i,total} - h_{i,jet} - h_{i,sled} = l_{cut} \times \sin(\gamma) - h_{i,jet} \quad (B.6)$$

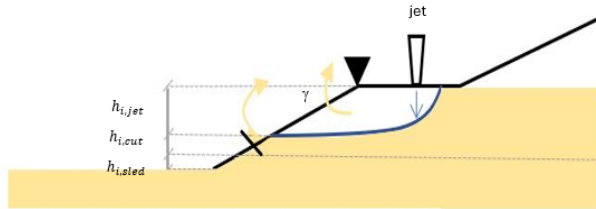


Figure B.6.: Cutting layer thickness generated prior to loading through the suction pipe (adopted from Janssen, 2023) (based on modified concepts presented in Miedema *et al.*, 2007; Van Rhee, 2017).

A comprehensive analysis of the production mechanisms, including both cutting and jetting processes, as well as the forces acting on the suction pipe and draghead of a TSHD, is presented by ter Meulen (2018) through a physics-based study of vessel resistance during the trailing stage.

In a TSHD, high-pressure water jets are employed to mobilize and loosen compacted seabed sediments. This jetting action increases the density of the suspended sediment, enhancing its entrainment into the suction pipe. The mass flux at the draghead is determined by the density of the water jets, sediment properties, and flow dynamics within the dredge intake system. In the context of TSHD dredging, the mass flux M_s represents the rate at which sediment mass is transported through the system or specific regions, such as from the seabed into the dredge intake, along the pipeline, or during sediment discharge (Van Rhee, 2017).

$$M_s = \rho_s \times (1 - n_0) \times h_{i,jet,vs} \times w_c \times v_t \times n_n \quad (B.7)$$

where the Vlasbom jet penetration depth ($h_{i,jet,vs}$) is calculated based on (Vlasbom, 2003).

The mass flux is converted into a density term ($\rho_s \times (1 - n_0)$) and a volume term ($h_{i,jet,vs} \times w_c \times v_t$). Therefore, the penetration depth is calculated as follows (Van Rhee, 2017).

$$h_{i,jet,vs} = \frac{M_s}{\rho_s \times (1 - n_0) \times w_c \times v_t \times n_n} \quad (B.8)$$

The cavity width (w_c) is calculated in two ways.

- $w_c = D_n$, cavity width equals the nozzle diameter in dredging cohesive soils as clay layers.
- $w_c = \begin{cases} h_{i,jet,vs} & \text{if } h_{i,jet,vs} < w_{c,max} \\ w_{c,max} & \text{otherwise} \end{cases}$, cavity width equals the jet layer thickness ($h_{i,jet,vs}$) if $h_{i,jet,vs}$ is lower than the maximum cavity width ($w_{c,max}$) which can be calculated by dividing the visor width by the number of nozzles ($w_{c,max} = w/n_n$).

Total penetration depth based on Vlasbom ($h_{i,total,vs}$) is calculated as follows based on the visor length (l_{visor}), sled length (l_{sled}), and visor angle (γ).

$$h_{i,total,vs} = l_{visor} \times \sin(\gamma) \quad (B.9)$$

The sled penetration depth ($h_{i,sled,vs}$), cut penetration depth ($h_{i,cut}$), and jet penetration depth ($h_{i,jet,vs}$) based on Vlasbom are calculated as follows by default (Vlasbom, 2003).

$$h_{i,sled,vs} = (l_{visor} - l_{sled}) \times \sin(\gamma) \quad (B.10)$$

$$h_{i,cut} = (h_{i,total,vs} - h_{i,sled,vs} - h_{i,jet,vs}) \quad (B.11)$$

$$h_{i,jet,vs} = h_{i,jet,vs} \quad (B.12)$$

However, if the jet penetration depth of Van Rhee ($h_{i,jet,vs}$) method meets the following conditions, the values for equations above are updated as follows.

$$\begin{cases} \begin{aligned} & \text{if } h_{i,jet,vs} > h_{i,total,vs} \\ & h_{i,cut} = 0.001 \\ & h_{i,sled,vs} = 0.001 \\ & h_{i,jet,vs} = h_{i,total,vs} \end{aligned} & \text{if } h_{i,jet,vs} > (h_{i,total,vs} - h_{i,sled,vs}) \\ \begin{aligned} & h_{i,cut} = 0.001 \\ & h_{i,sled,vs} = h_{i,jet,vs} - h_{i,jet,vs} \\ & h_{i,jet,vs} = h_{i,jet,vs} \end{aligned} & \end{cases} \quad (B.13)$$

This indicates that limitations in the cavity width constrain the maximum achievable jet production at relatively low trailing velocities for a TSHD. At velocities below 1 m/s, the production rate is generally underestimated, while at higher velocities it may be overestimated. The trailing velocity that maximizes jet production occurs when the cavity reaches its maximum width $w_{c,max}$.

For a TSHD, jet production refers to the use of high-pressure water jets to loosen sediment and improve suction efficiency. The total jet production is calculated as the sum of sand production Q_{sand} , water production Q_{water} , and the jet flow discharge at the working point $Q_{jet,wp}$.

$$Q_{jet} = Q_{sand} + Q_{water} + Q_{jet,wp} \quad (B.14)$$

Where the sand and water production is calculated as follows, and the jet flow discharge is obtained from the characteristics of the jet water pumps.

$$Q_{water} = \frac{Q_{sand}}{(1 - n_0)} \times n_0 \quad (B.15)$$

$$Q_{sand} = \frac{M_s}{\rho_s} \quad (B.16)$$

Jet pumps can be installed both on the draghead and along the suction pipe of a TSHD. Those mounted on the draghead are positioned near the sediment intake, where they help disaggregate compacted material and promote a uniform flow into the dredge system. In contrast, jet pumps along the suction pipe maintain material transport and prevent blockages within the pipeline, ensuring uninterrupted operation.

EROSION PRODUCTION

In a TSHD, erosion production refers to the volume of sediment loosened or dislodged from the seabed through the combined action of the draghead and its water jets. High-pressure jets directed at the seabed near the draghead mobilize sediment, creating a slurry of water and particles. The draghead, equipped with teeth, blades, or rippers, mechanically breaks up and loosens seabed material as it is towed along the bottom. The combined hydraulic and mechanical erosion maximizes the material available for suction. Erosion production is influenced by factors such as jet pressure, slurry flow rate, draghead geometry, sediment properties, trailing speed, and visor configuration. However, due to the difficulty of accurately quantifying this component, erosion production is neglected in this study when calculating total excavation production.

B.2. TOTAL DREDGING DURATION OF A WID

A WID operates continuously, pausing dredging only when tidal conditions are unfavorable. The tidal amplitude t_{tidal} denotes the duration of a full tidal cycle. Dredging is typically conducted during the outgoing tide, approximately half of the tidal window, when natural currents and tidal motion assist in re-mobilizing the fluidized sediment.

$$t_{dredging,wid} = \frac{t_{tidal}}{2} - t_{sailing,wid} \quad (B.17)$$

The total production of a WID is estimated based on the effectiveness of the jetting process in penetrating the sediment bed, as well as the area production, which depends on the vessel's sailing speed and the width of the area being treated by the jet bar (Miedema, 2019). Additional factors, such as sediment type, the distance between the High Energy Environment (HEE) and Low Energy Environment (LEE), and tidal amplitude, also significantly affect the vessel's production rate during project execution (Prins, 2024).

Sediment dredging with a WID is carried out using a jet system consisting of two jet pipes and a horizontal jet beam fitted with downward-pointed nozzles. Large volumes of low-pressure water are injected to fluidize the sediment and transport the resulting mixture out of the system. Key parameters for effective operation include the total power of the jet pumps, the stand-off distance between the jet beam and the sediment bed, and the vessel's sailing speed.

The theoretical model proposed by Miedema (2019) discussed the fundamentals of jet pump systems and how the penetration depth of jets in sediment beds can be quantified. Empirical models define some restrictive boundaries on the sediment layer densities, sediment types, distance between LEE and HEE, and tidal amplitudes on production estimation. The total production is achieved through jet and erosion production, while jet production is the main term being analyzed in this chapter. Therefore, the excavation production is calculated by multiplying the area production Q_{area} by the nozzle penetration depth d_p as follows (Miedema, 2019).

$$Q_{total} = Q_{area} \times d_p \quad (B.18)$$

where (Q_{area}) and (d_p) are obtained as follows.

$$Q_{area} = v \times w_{jet.beam} \quad (B.19)$$

$$d_p = \sqrt{\frac{\alpha \times C_c \times A_{nozzle} \times u_{jet.beam} \times u_{nozzle}}{\rho_{particle} \times (1 - n_0) \times v^2}} \quad (B.20)$$

The water velocity in a jet beam $u_{jet.beam}$ depends on the total flow coming from the jet pump and the dredging area A_{jet} , while the water velocity through each nozzle u_{nozzle} is affected by pressure differences Δp_{nozzle} in the nozzle and the water density ρ_{water} .

$$u_{jet.beam} = \frac{Q_{jet}}{A_{jet}} \quad (B.21)$$

$$u_{nozzle} = \sqrt{\frac{2 \times \Delta p_{nozzle}}{\rho_{water}}} \quad (B.22)$$

The pressure difference in a nozzle is determined as follows.

$$\Delta p_{nozzle} = \frac{1}{2} \times \rho_{water} \times \left(\frac{4 \times Q_{jet}}{C_c \times \pi \times n_n \times D_{nozzle}^2} \right)^2 \quad (B.23)$$

where C_c shows the contraction coefficient of the jets (the ratio of the actual cross-sectional area of the jet in the vena contracta (the narrowest point of the flow) to the cross-sectional area of the nozzle or orifice), n_n shows the number of nozzles, and D_{nozzle} is the diameter of the nozzle.

According to empirical data, the calculated penetration depth is affected by the grain size density, bulk density, and a factor related to the distance between LEE and HEE. The penetration depth is multiplied by the coefficients based on the distance and density factors. Moreover, a limiting factor for tidal amplitude is taken into account when estimating the production. These limiting factors are multiplied by the total production. These factors represent the fraction of the production rate that is transported to the HEE. Besides, it can be implied as empirical knowledge on how the transport distance of sediment, sediment properties, and tidal amplitude influence the efficiency of excavating materials using a WID. The factors are used empirically and can be accessed internally.

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LIST OF PUBLICATIONS

PUBLICATIONS RELATED TO THIS DISSERTATION

Published Journal Articles

- A. Sepehri, A. Kirichek, S. Van der Werff, E. Baart, M. Van den Heuvel, and M. Van Koningsveld (2024c). "Analyzing the interaction between maintenance dredging and seagoing vessels: a case study in the Port of Rotterdam". In: *Journal of Soils and Sediments*, pp. 1–11. DOI: 10.1007/s11368-024-03847-1
- A. Sepehri, A. Kirichek, M. Van den Heuvel, and M. Van Koningsveld (2024b). "Smart, sustainable, and circular port maintenance: A comprehensive framework and multi-stakeholder approach". In: *Journal of Environmental Management* 370, p. 122625. ISSN: 0301-4797. DOI: 10.1016/j.jenvman.2024.122625
- A. Sepehri, A. Kirichek, M. Van den Heuvel, M. de Geus, and M. Van Koningsveld (2026). "Sustainable port maintenance: dredging equipment selection in time-emission trade-offs". In: *Results in Engineering*, p. 109247. DOI: 10.1016/j.rineng.2026.109247

Under Review Journal Articles

- A. Sepehri, A. Kirichek, M. Van den Heuvel, M. de Geus, and M. Van Koningsveld (2026). "Sustainable port maintenance: dredging equipment selection in time-emission trade-offs". In: *Journal of Soils and Sediments*.

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- A. Sepehri, A. Kirichek, and M. Van Koningsveld (2023). "Sustainable port maintenance strategies: trade-offs between dredging cost and port call efficiency". In: *13th International SedNet Conference*. URL: <https://sednet.org/wp-content/uploads/2023/08/3.9-Sustainable-port-maintenance-strategies-trade-offs-between-dredging-cost-and-port-call-efficiency.pdf>
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- A. Sepehri, H.R. Vandchali, A.W. Siddiqui, and J. Montewka (2022). "The impact of shipping 4.0 on controlling shipping accidents: A systematic literature review", In: *Ocean Engineering*. <https://doi.org/10.1016/j.oceaneng.2021.110162>
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Ports are vital nodes in global supply chains, yet their accessibility is constantly challenged by natural sedimentation processes. Maintenance dredging is essential to ensure safe and efficient navigation, but decision-making in this domain has traditionally been driven by cost and time considerations alone.

This dissertation introduces a novel framework that makes three increasingly important value dimensions - smartness, sustainability, and circularity - measurable and operational. By combining data-driven analysis, physics-based modeling, and system-oriented methods, the research translates these concepts into quantitative indicators that can support real-world decision-making.

Through applications such as analyzing seagoing-dredging interactions, quantifying emissions across dredging operations, and evaluating sediment reuse strategies, this work demonstrates how port authorities and contractors can better understand trade-offs and align their objectives. The proposed event-based approach enhances transparency and enables comparison across different operational scales.

By bridging the gap between conceptual ambitions and practical tools, this dissertation provides a foundation for more informed, efficient, and environmentally responsible port maintenance strategies.

