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From linear to circular port maintenance dredging: a case study of beneficial reuse of dredged material for dike reinforcement

Arash Sepehri[1] · Alex Kirichek[1] · Marcel van den Heuvel[2] · Mark van Koningsveld[1,2]

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Abstract

Purpose Maintenance dredging is essential for navigability but often follows linear "extract–dispose" practices that lead to material loss and offshore impacts. This study develops a structured framework to quantify circularity in maintenance dredging and evaluates how sediment reuse can contribute to regenerative port management. The central question is how circularity, through material retention, reuse, and reduced environmental impact, can be measured and compared against conventional offshore disposal strategies.

Methods A circularity assessment framework was developed by integrating circular economy principles with process-based modeling of dredging operations. The framework combines operational, environmental, and material performance dimensions and applies the Material Re-utilization Score (MRS) and Material Circularity Indicator (MCI) to quantify sediment retention and flow quality. A discrete-event simulation using OpenCLSim was coupled with physics-based power, energy, and emission models to analyze two scenarios at the Port of Delfzijl (the Netherlands): (1) linear offshore disposal with a Trailing Suction Hopper Dredger, and (2) circular reuse through discharge into clay-ripening compartments for dike reinforcement. Event tables were used to structure activities, operational durations, energy use, emissions, and sediment state transformations.

Results The circular scenario achieved substantial material recovery (MRS = 0.87; MCI = 0.78), whereas offshore disposal resulted in zero circularity. Despite higher establishment costs and longer total project duration due to ripening, the circular scenario required 23% less operational energy and produced fewer emissions, primarily because of shorter sailing distances. Operational dredging time was comparable between scenarios, demonstrating that circularity does not inherently reduce efficiency. The event-table approach revealed explicit trade-offs between logistics, material degradation, energy use, and utility of the final clay product. Overall, transitioning to circular dredging requires upfront investment but yields long-term value through resource retention and reduced dependence on offshore disposal.

Conclusions This study provides a quantitative framework for assessing circularity in maintenance dredging and demonstrates its practical applicability through a real port case. Circular reuse of dredged sediment offers measurable material and environmental benefits despite increased preparation requirements. The framework enables evidence-based comparison of linear and circular strategies, supporting decision-makers seeking to advance regenerative, resource-efficient, and sustainable port maintenance practices.

Keywords Maintenance dredging · Circular economy · Beneficial reuse · Circularity assessment · Sustainable port operations

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✉ Arash Sepehri
a.sepehri@tudelft.nl

[1] Section of Rivers and Ports, Department of Hydraulic Engineering, Faculty of Civil Engineering and Geosciences, Delft University of Technology, Stevinweg 1, Delft 2628CN, the Netherlands

[2] Van Oord Dredging and Marine Contractors, Schaardijk 211, Rotterdam 3063NH, the Netherlands

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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 disposed of 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 (Laboyrie et al. 2018; Van Koningsveld et al. 2023).

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. 2024).

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 disposal using a Trailing Suction Hopper Dredger (TSHD) and follows the traditional “extract–transport–dispose” 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 (Mulder et al. 2007; Korhonen et al. 2018). 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 Material Circularity Indicator (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 (Moraga et al. 2019; Kristensen and Mosgaard 2020). 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 (Niero and Kalbar 2019; Sepehri et al. 2023).

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, 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 (MFA), Life Cycle Assessment (LCA), and Circularity Indicators (C-Indicators) that quantify retained material value or recovery potential (De Pascale et al. 2021; de Souza et al. 2024; Muñoz et al. 2024). The reuse of excavated soil, recycled aggregates, and demolition 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 (Maletić et al. 2019; Spadaro and Rosenthal 2020; Almokdad and Zentar 2023). 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 (Ulibarri et al. 2020; Dorleon et al. 2024; Sepehri et al. 2024). By adapting lessons from these sectors, this study develops a dredging-specific approach that integrates material flow reasoning with circularity metrics. In current practice, beneficial reuse of dredged material is already applied in several forms, including beach nourishment, land reclamation, habitat restoration (e.g., intertidal flats and wetlands), and, in some cases, as secondary construction material such as embankments, road base, or engineered fill. These applications demonstrate an increasing shift from disposal-oriented management toward resource-oriented strategies. This enables both qualitative interpretation and quantitative comparison of alternative dredging scenarios.

Although beneficial reuse of dredged sediments is increasingly recognized as a promising circular strategy, wider implementation remains constrained by uncertainties regarding technical feasibility, environmental performance, regulatory acceptance, and long-term material quality. Pilot and demonstration projects therefore play a critical role in validating reuse pathways, reducing stakeholder uncertainty, and providing evidence for scaling circular sediment management practices. Initiatives such as clay ripening projects in the Netherlands illustrate how demonstration cases can support the transition from conceptual beneficial reuse approaches toward operational implementation by evaluating material behavior, environmental impacts, and practical applicability under real conditions.

Building on these conceptual foundations, the remainder of this paper presents the development and application of a circularity assessment framework. Section 2 elaborates on the research methodology used to quantify the circularity of maintenance dredging projects and simulate different scenarios. Section 3 analyzes the results obtained from real-world data when simulating two separate scenarios and the proposed circularity indicators. Section 4 discusses the findings in more detail, addresses theoretical and managerial implications, and proposes future research directions.

2 Methodology

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 disposal or reallocation, whereas circular dredging seeks to retain and reuse dredged sediments through beneficial use pathways. These pathways may include onshore applications, such as dike reinforcement, land reclamation, and construction materials, as well as in-water applications, including habitat restoration, nourishment, and morphological reshaping. Such approaches aim to preserve material value and reduce dependence on primary resources. However, comparing these approaches is challenging because circular strategies introduce additional processes, material transformations, and temporal considerations. 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.

2.1.1 Operational performance

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 $T_{decomissioning}$, which include the activities to render the sediment reusable and the removal of supporting infrastructure (See Eq. 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. Operational and environmental factors influence the duration of each activity. Sailing time depends on the distance between dredging and disposal sites, vessel speed, and loading conditions. For harbor maintenance projects, sailing duration is often primarily determined by route length and operational logistics. However, for inland waterway dredging projects, additional factors such as lock passages, bridge restrictions, current velocity, water levels, traffic intensity, and navigation constraints may substantially influence sailing time and consequently affect project duration, energy consumption, and emissions. 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 the production rate include sediment properties, draghead efficiency, and the performance of the dredge pumps and associated pipeline system. The loading process can be modeled by distinguishing three stages: cutting, jetting, and erosion, each contributing differently to the overall production rate. 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.

$$T_{total} = T_{establish} + \sum_{n=1}^{nr\_dredging\_cycles} T_{cycle} + T_{decommissioning} \quad (1)$$

The estimation of the 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 Eq. 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 $C_{decomissioning}$ 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.

$$C_{total} = C_{establish} + \sum_{n=1}^{nr\_dredging\_cycles} C_{cycle} + C_{decommissioning} \quad (2)$$

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 CO_2 output.

2.1.2 Environmental performance

To assess the environmental performance of different dredging scenarios, total energy consumption and CO_2 emissions are considered the primary environmental indicators in this study. Other relevant indicators include turbidity, which is a major concern due to its effects on water quality and marine ecosystems, as well as the potential release and resuspension of contaminants from disturbed sediments. In addition, underwater sound can influence environmental impact assessments by affecting marine fauna and habitat conditions.

A quantifiable method for estimating turbidity in dredging operations has been proposed by Becker et al. (2015) that 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 Eq. 3). Total energy consumption E_T is calculated by aggregating the energy consumed per activity for all the dredging cycles (See Eq. 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.

To extend the applicability of the model beyond dredging and disposal-at-sea operations, inland and alternative sediment handling processes (such as unloading at quays, temporary storage, and final repository management) should be represented through a structured event-based description of activities. In such cases, energy use can similarly be quantified by defining operational events with associated power demand and duration, consistent with the event table approach introduced later in this study. This ensures that all relevant handling steps in the sediment transport chain can be incorporated in a consistent way.

$$E_{act} = \int_{t_0}^{t_1} P_{act}(t)\,dt \tag{3}$$

$$E_T = \sum_{i=1}^{nr\_activities} \int_{t_{0,i}}^{t_{1,i}} P_{act,i}(t)\,dt \tag{4}$$

Emissions EM_T are then estimated by Eq. (5) 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.

$$EM_T = E_T \times SFC \times EF \tag{5}$$

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 (Miedema 2019; van der Bilt 2019; Lamers 2022; Janssen 2023; 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 1.

Table 1 Active energy consumers per activity in a TSHD

Energy consumer	Activity			
	Sailing empty	Loading	Sailing full	Discharging
Propulsion	✖	✖	✖	✖
Dredge pumps		✖		
Jet pumps		✖		✖
Bow thrusters				✖
Board net	✖	✖	✖	✖

Dredge pumps, located outside the vessel's hull, roughly halfway on the suction pipe, are primarily responsible for generating suction pressure to lift the sediment-water mixture. Jet pumps 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 study, 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 requirement of the board net is assumed to remain constant throughout the dredging cycle.

2.1.3 Material performance

Reused dredged fine-grained sediment often requires time to mature into reusable clay, meaning that material availability is not immediate. 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. Material Re-utilization Score (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).

$$MRS = \frac{[(IR).2 + (RC).1]}{3} \times 100 \tag{6}$$

2. Material Circularity Indicator (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. The first component, the quantity (or flow) component L/L_{av}, represents how the volume of sediment directed to reuse in each period compares to an average or reference flow level. In this context, Lrefers to the actual reused sediment volume, while L_{av} represents a reference or baseline volume over a comparable period. The second component, the utilization intensity component U/U_{av}, reflects how effectively the reused sediment is applied in its intended function (e.g. dike reinforcement, land reclamation, or construction use). Here, U represents the actual functional use (e.g. volume effectively incorporated into a beneficial application), while U_{av} represents a reference level of use for comparable materials in similar applications. Together, these components describe both the amount of sediment reused and the effectiveness of its application in practice, providing a more operational interpretation of sediment utility in circular dredging contexts.

$$X = \left(L/L_{av}\right) \times \left(U/U_{av}\right) \tag{7}$$

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.

$$LFI = \frac{M_{reallocation}}{M_{reallocation} + M_{loss.reuse}} \tag{8}$$

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.

$$MCI_p = 1 - LFI \times F(X), \quad F(X) = \frac{0.9}{X}, \quad MCI = (0, MCI_p) \tag{9}$$

As $F(X)$ is only affecting the linear part of the material flow, the MCI takes the value 1 when no waste is generated during dredging and dumping, irrespective of the sediment utility. In other cases, $F(X)$ is designed to penalize sediment with a short lifetime and poor utilization, and vice versa.

In this context, TDS (tons dry solids) 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.

2.2 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, where additional code developed for production and energy consumption estimation is stored in a private GitHub repository and can be shared upon request (Van Koningsveld et al. 2019; de Boer et al. 2023). 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 2 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 (See Fig. 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 (See Fig. 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 (Kleirijperij 2024).

Table 2 Perspectives for circular maintenance dredging

Perspective	Focus	Requirements	Data and attributes
Scale	Time and space definition	• Define system boundaries and spatial resolution • Determine dredging duration and operational time steps • Map vessel movement patterns	• Geographic coordinates of sites, routes, and circular system boundaries • Start and end time per activity • Activity sequence identifiers
Conditions	Environmental and operational drivers	• Characterize sediment properties, hydrodynamics, and vessel specifications • Incorporate operational limits	• Sediment density, grain size, and water depth • Vessel speed and pump power • Intermediate performance calculations
Behavior	Sequence and scheduling of activities	• Identify operational agents (vessels and 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	-

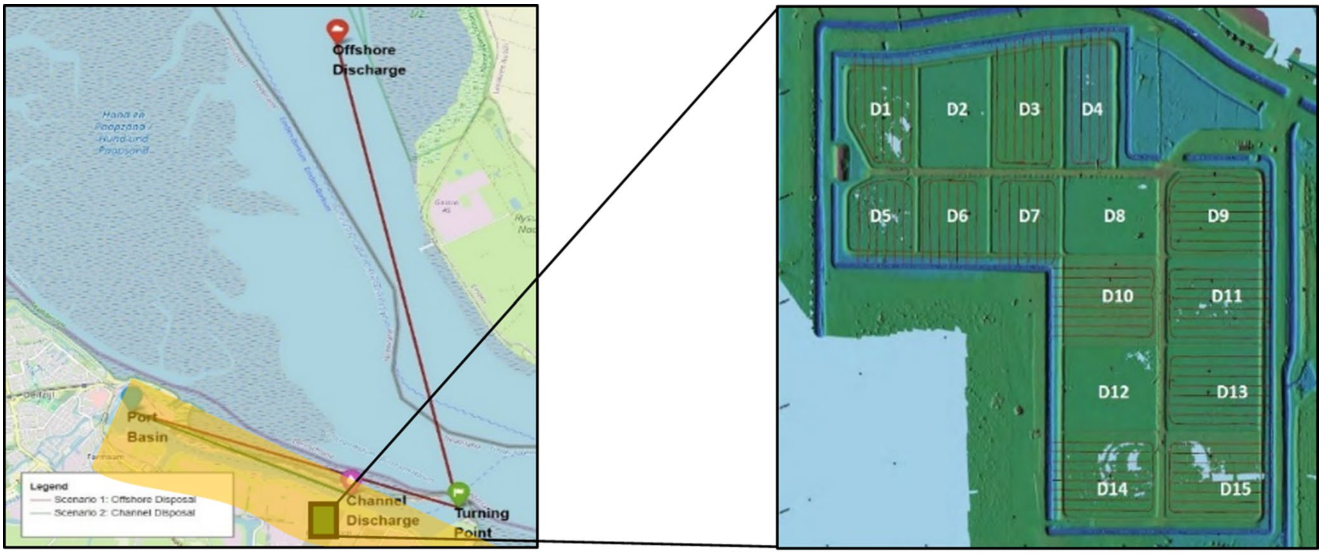
This reuse pathway is selected as the reference beneficial application because dike reinforcement is a well-established, technically validated, and regionally high-demand use case for fine dredged sediments in the Netherlands, as also demonstrated in prior Dutch circular sediment and building-with-nature initiatives. While other beneficial reuse options exist (such as land reclamation or construction material use), they are not explicitly considered in this case study in order to maintain a focused and policy-relevant comparison framework.

Two scenarios are established to assess the influence of circularity on key performance indicators. The first scenario represents conventional linear maintenance dredging in the Port of Delfzijl, involving repeated sailing between the port basin, a turning point, and offshore disposal 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 m³ of sediment was pumped into ripening compartments, and another between 11 and 13 July 2018, during which approximately 89,000 m³ was pumped into ripening compartments. In this case, the dredged material was discharged into clay ripening compartments using an onboard discharge pump.

The circular system boundary, illustrated as the orange-shaded area in Fig. 1a, defines the spatial system within which sediment handling and reuse are assessed in relation to circular port maintenance. It includes the port basin, navigation channel, and designated sediment placement or reuse areas, such as offshore disposal sites and onshore or in-channel ripening compartments. This boundary must be explicitly defined a priori by the client, contractor, or analyst, as circularity assessments are inherently dependent on the spatial and temporal limits of the system. Without such definition, sediment could theoretically remain part of a broader geological cycle, making the concept of circularity analytically unbounded.

In addition to spatial limits, temporal boundaries are equally important, as they determine whether delayed reuse pathways (e.g. clay ripening over several decades) are considered within the scope of circularity assessment. In this study, Scenario 1 (offshore disposal) lies outside the defined circular system boundary, whereas Scenario 2 (channel discharge and ripening compartments) is included due to its potential for local beneficial reuse within a relevant time frame.

A multi-criteria trade-off analysis is employed to compare both scenarios in terms of cost, duration, energy consumption, and emissions. Emissions EM_T are estimated based



(a) (b)

Fig. 1 Schematic picture of the Kleirijperij project on (**a**) dredging, discharging, and reusing activities (The orange-shaded area indicates the circular system boundaries); and (**b**) ripening compartments. (Source: OpenStreetMap)

on fuel use and corresponding emission factors, capturing operational fuel-related CO_2 emissions of the dredging vessels. Other environmental impacts associated with dredging activities, such as combustion-related non-CO_2 emissions, turbidity, and sediment disturbance effects, are not explicitly quantified in this study. While these impacts may partially offset or differ between scenarios, they are assumed to be of comparable magnitude in both cases due to the use of the same dredging equipment and operational processes and are therefore not included in the comparative assessment. However, the relative differences in fuel consumption are used as a proxy for differences in overall operational environmental burden.

Additional system-level effects, such as land occupation, soil gain or loss, and associated socio-economic implications (e.g. local economic activity or employment), are not quantified in detail, as they fall outside the primary objective of this study. However, they are qualitatively acknowledged as potential co-benefits or trade-offs of sediment reuse strategies, particularly in Scenario 2. Their inclusion would imply an extension of the current system boundary from a purely operational dredging system to a broader socio-economic and land-use system perspective.

Additionally, a circularity index is calculated for Scenario 2 to assess its contribution to circular dredging practices. The findings indicate that the spatial configuration of operational locations and vessel capacity significantly influence total project duration, and consequently energy use and fuel-related emissions. The indicators used in this analysis are determined by vessel characteristics, sediment properties, and project configuration. To simplify the assessment, average power requirements of the TSHD are derived from open-source data, and project durations are estimated through simulations of vessel movements between the operational locations shown in Fig. 1a.

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 3).

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. In addition to CO_2 emissions, the environmental performance indicator in this study is deliberately limited to operational fuel-related greenhouse gas emissions, as these dominate the comparative differences between scenarios at the vessel scale. Other environmental impacts, such as non- CO_2 greenhouse gas emissions, water quality impacts (e.g.

Table 3 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]	Total CO_2 emission [tons]	End MRS	End MCI
Scenario 1 (offshore disposal)	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 the 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
		…	…	…	…	…	…	…	…	…	…	…
		sailing empty to the turning point 79	15 Apr 2018 19:16	15 Apr 2018 19:41	discharging site to turning point	0.42	376.91	2129	899.61	0.77	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	53.02	2129	126.55	0.10	0	0
		loading 79	15 Apr 2018 19:44	15 Apr 2018 20:58	port basin	1.23	1101.62	3479	4296.56	3.68	0	0
		sailing full to the turning point 79	15 Apr 2018 20:58	15 Apr 2018 21:02	port basin to turning point	0.07	64.21	2129	153.27	0.13	0	0
		sailing full to the discharging site 79	15 Apr 2018 21:02	15 Apr 2018 21:33	turning point to the discharging site	0.51	456.48	2129	1089.53	0.93	0	0
		discharging offshore 79	15 Apr 2018 21:33	15 Apr 2018 21:39	discharging site	0.10	89.20	409	40.90	0.03	0	0
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	0.99	0.68
		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	0.68
		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	0.68
		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	0.68
		…	…	…	…	…	…	…	…	…	…	…
		sailing empty 43	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	0.99	0.68
		loading 43	7 Apr 2018 00:02	7 Apr 2018 01:16	port basin	1.23	1101.62	3479	4296.56	3.97	0.99	0.68
		sailing full 43	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	0.68
		discharging 43	7 Apr 2018 01:20	7 Apr 2018 01:53	storage compartments	0.54	489.60	1199	658.11	0.56	0.99	0.68
		…	…	…	…	…	…	…	…	…	…	…
		sailing empty 44	11 Jul 2018 00:00	11 Jul 2018 00:02	storage compartments to the port basin	0.04	41.71	2129	99.55	0.09	0.87	0.69

Table 3 (continued)

Scenario	Event		Attributes									
	Event ID	Event name	Operational performance					Environmental performance			Material performance	
			Start time	End time	Spatial location	Duration [h]	Cycle cost [€]	Total power [kW]	Total energy [kWh]	Total CO_2 emission [tons]	End MRS	End MCI
		loading 44	11 Jul 2018 00:02	11 Jul 2018 01:16	port basin	1.23	1101.62	3479	4296.56	3.97	0.87	0.69
		sailing full 44	11 Jul 2018 01:16	11 Jul 2018 01:20	port basin to storage compartments	0.05	50.51	2129	120.57	0.11	0.87	0.69
		discharging 44	11 Jul 2018 01:20	11 Jul 2018 01:53	storage compartments	0.54	489.60	1199	658.11	0.56	0.87	0.69
		…	…	…	…	…	…	…	…	…	…	…
		sailing empty 79	13 Jul 2018 00:00	13 Jul 2018 00:02	storage compartments to the port basin	0.04	41.71	2129	99.55	0.09	0.87	0.69
		loading 79	13 Jul 2018 00:02	13 Jul 2018 01:16	port basin	1.23	1101.62	3479	4296.56	3.97	0.87	0.69
		sailing full 79	13 Jul 2018 01:16	13 Jul 2018 01:20	port basin to storage compartments	0.05	50.51	2129	120.57	0.11	0.87	0.69
		discharging 79	13 Jul 2018 01:20	13 Jul 2018 01:53	storage compartments	0.54	489.60	1199	658.11	0.56	0.87	0.69

turbidity, suspended sediment dispersion), and ecological disturbance effects, are not quantified in this table, as they require site-specific hydrodynamic and ecological modelling beyond the scope of the present operational assessment.

Figures 2 and 3 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 disposal 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.

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 (EcoShape 2023; Kleirijperij 2024). The overall project timeline is presented in Fig. 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.

Both the MRS and MCI vary throughout the project, as they are directly influenced by the reusability 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

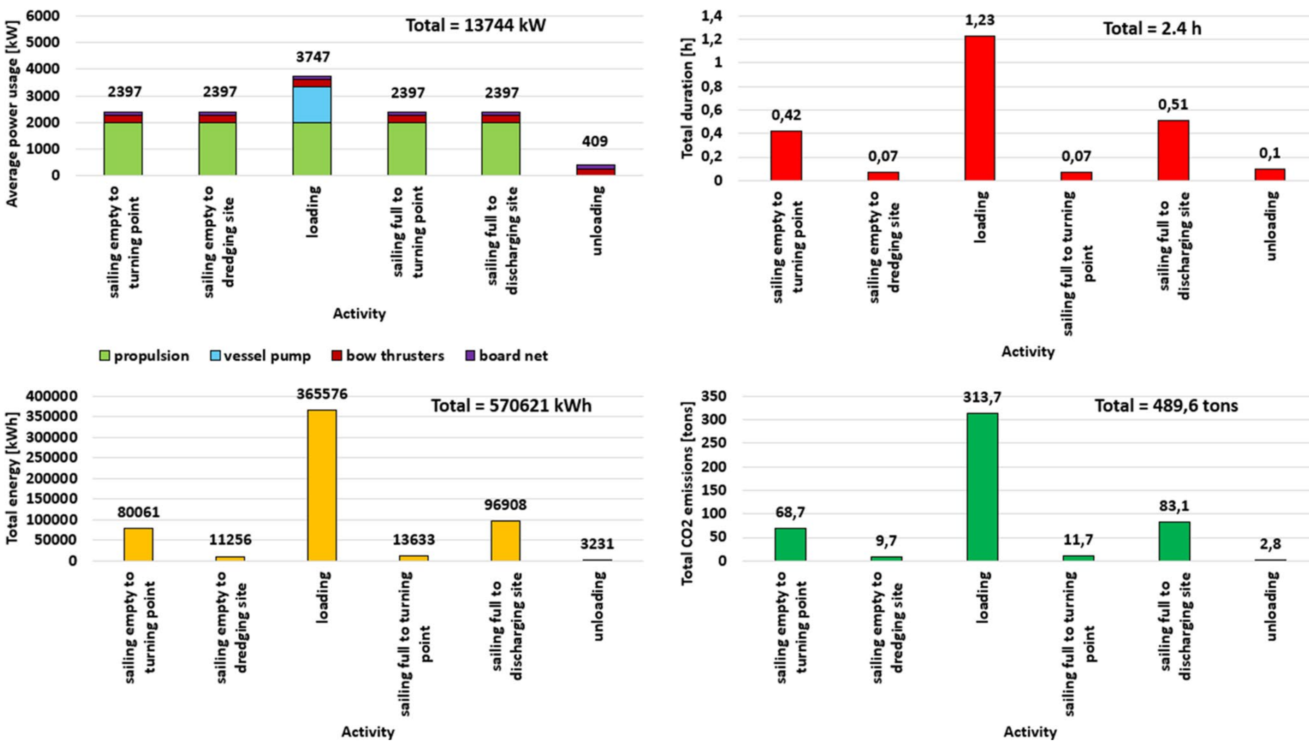


Fig. 2 Operational and environmental performance trade-offs for Scenario 1 (offshore disposal)

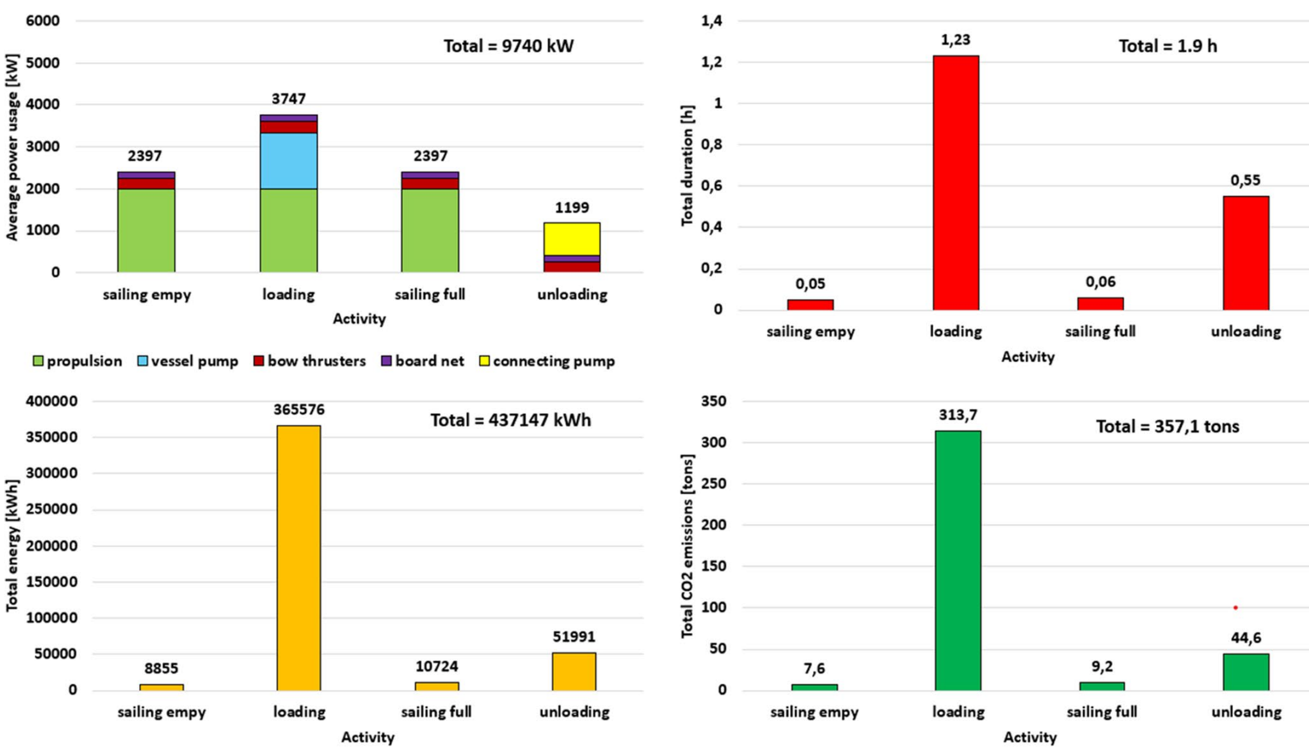


Fig. 3 Operational and environmental performance trade-offs for Scenario 2 (sediment reuse)

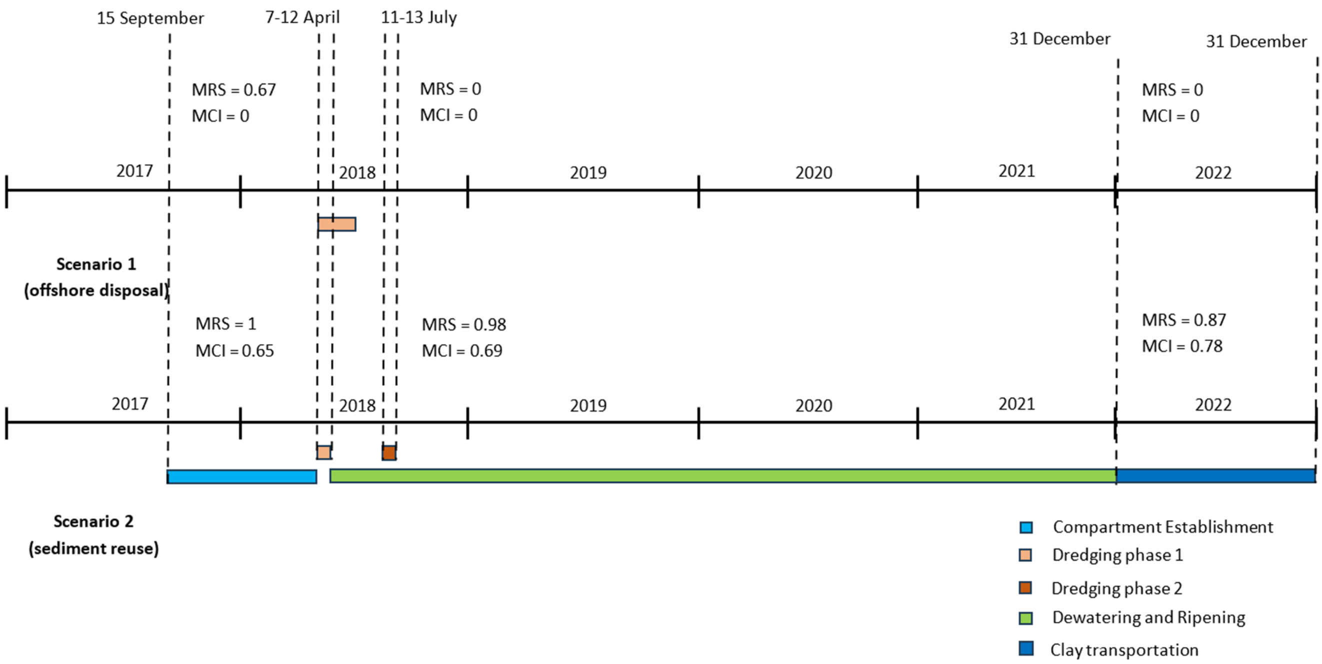


Fig. 4 Operational and material performance comparison for both scenarios

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 4 shows an event table for sediment state changes during each scenario.

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 Fig. 5 provides a comparative overview of the two dredging scenarios, offshore disposal (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.

Despite the considerably higher establishment cost and longer duration of Scenario 2 compared to the offshore disposal 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

Table 4 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 disposal)	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 the 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 21:02	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 21:02	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	0.67
		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
	…	…	…	…	…	…	…	…	…	…	…	…	…
	Sediment batch 43	sailing empty 43	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 43	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 43	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 43	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
	Sediment batch 1-43	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

Table 4 (continued)

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
	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 01:16	port basin	1.23	1	0.94	0.98	0.87	0.35	0.68	0.69
		sailing full 44	11 Jul 2018 01:16	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
	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮
	Sediment batch 79	sailing empty 79	13 Jul 2018 00:00	13 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	13 Jul 2018 01:16	port basin	1.23	1	0.94	0.98	0.87	0.35	0.68	0.69
		sailing full 79	13 Jul 2018 01:16	13 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	13 Jul 2018 01:53	storage compartments	0.54	1	0.94	0.98	0.87	0.35	0.68	0.69
	Sediment batch 1-79	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

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.

While this study is demonstrated on a harbor-based dredging case, the proposed event-based framework and circularity indicators are not inherently limited to coastal or port environments. For inland waterways, riverine dredging, or reservoir sediment management, the same structure can be applied by redefining the system components (e.g. replacing navigation channels and marine disposal sites with river reaches, floodplains, or inland reuse locations). Similarly, vessel-based operations may be substituted with barges, excavators, or hydraulic transport systems depending on the local context. The event table structure remains applicable as long as sediment movement can be discretized into operational activities with measurable duration, energy use, and material flows, allowing the method to be transferred to inland beneficial use strategies.

4 Discussion

4.1 Transition from linear to circular port maintenance

The comparative assessment of offshore disposal 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 disposal) 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

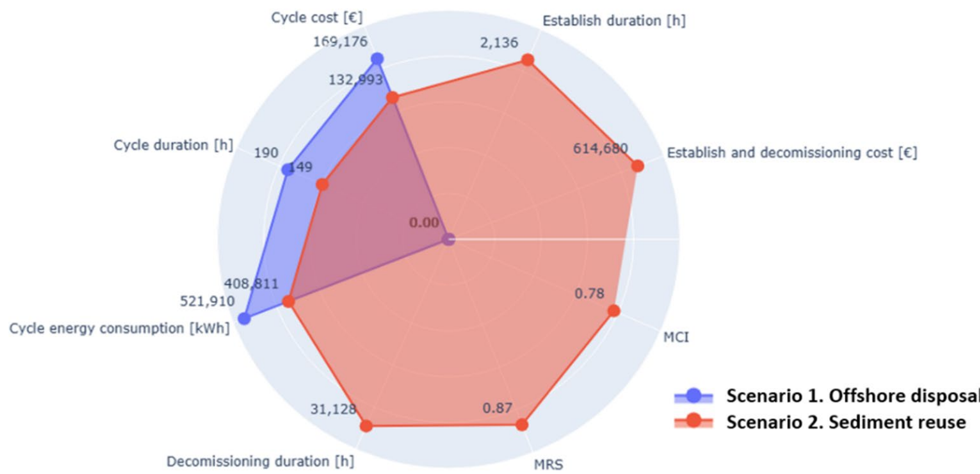


Fig. 5 Scenario comparison using a normalized bar chart

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.

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-disposal cycle. This result is primarily attributed to the shorter sailing distance to the near-shore ripening compartments versus the distant offshore disposal 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 disposal 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.

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 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 disposal 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 disposal, 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 disposal 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 circular economy principles within a process-based modeling framework for hydraulic engineering. It bridges the conceptual gap between circular economy metrics 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.

Author contribution Arash Sepehri Conceptualization; Methodology; Formal Analysis; Simulation Development; Data Curation; Writing - Original Draft; Visualization. Alex Kirichek Supervision; Conceptual Guidance; Validation; Writing - Review & Editing. Marcel van den Heuvel Conceptual Guidance; Validation; Writing - Review & Editing. Mark van Koningsveld Supervision; Methodological Feedback; Validation; Writing - Review & Editing.

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Declarations

Competing interests The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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