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Research paper

Sustainable port maintenance: Dredging equipment selection in time-emission trade-offs

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ABSTRACT

Maintenance dredging in ports and waterways is essential to ensure safe navigation. With increasing regulatory pressure on the maritime sector to reduce exhaust emissions, both dredging contractors and port authorities are seeking effective mitigation strategies. However, accurate emission estimates for maintenance dredging activities are still limited in the literature and often rely on experiential knowledge rather than scientific methodologies. This study suggests a method for estimating emissions and comparing alternative maintenance dredging strategies by quantifying trade-offs between project duration, energy consumption, and emissions. The method integrates vessel characteristics, project specifications, and sediment properties to allow for situation-specific, realistic assessments. A discrete-event simulation is used to evaluate two alternative scenarios, offering insights into the impact of key parameters on vessel selection and overall operational efficiency. The method is demonstrated using a case study of the Port of Ramsgate (UK), where estimated results are compared with real-world data for validation. Finally, the study outlines theoretical and managerial implications and suggests directions for future research.

1. Introduction

The increasing demand for waterborne transport has created a competitive environment for port authorities, driving them to enhance infrastructure and service quality, attract more clients, and handle higher cargo volumes. Terminal infrastructure and service levels play a crucial role in port selection by shipping companies. A key aspect of maintaining high-quality infrastructure is regular maintenance dredging, which ensures the safe navigation of large seagoing vessels [1]. High sedimentation rates in port basins and navigation channels can obstruct port operations, leading to partial or complete inaccessibility. Such disruptions not only impact cargo handling efficiency but also result in significant economic losses and reduced port reliability in an increasingly competitive market [27].

Port maintenance dredging is primarily carried out through three methods: (1) sediment reallocation, where material is collected from one area and discharged in another; (2) sediment re-mobilization, where natural currents redistribute the material from the dredging area; and (3) sedimentation mitigation, which involves measures to reduce sediment accumulation [2]. Among the commonly used equipment for maintenance dredging are the Trailing Suction Hopper Dredger (TSHD) and the Water Injection Dredger (WID), each employing fundamentally different working principles. A TSHD, typically used for sediment re-allocation, loads material into an onboard hopper using dragheads and suction pipes, and subsequently discharges the collected material at an offshore location. In contrast, a WID, primarily used for sediment remobilization, employs a jet beam connected to a jet pipe and pump to inject water into the sediment bed. This process fluidizes the sediments, which are then lifted into the water column and transported away by natural currents [10]. These two methods are discussed further in this study, as they form the basis for comparing alternative dredging strategies in terms of efficiency and environmental impact.

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

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equipment and methods that minimize dredging frequency and emissions, reflecting a more holistic approach that integrates economic, environmental, and social goals [18]. 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 [8]. 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 [24]. A diversity of studies has 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.

Laboyrie et al [12] presented a generic framework for estimating Greenhouse Gas (GHG) 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 CO_2 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 [20] examined the GHG 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 m^3 of sand for just one project, dredging emissions become a significant yet underreported 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.

De Roode et al [6] developed an emission model for TSHDs, detailing CO_2, 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 (CPPs), 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. Despite the fact that this study validates emissions during TSHD operation and explores reduction strategies, it simplifies real-world conditions by not accounting for the 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 [11] 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 CO_2 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 [25] 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 [13] and loading/unloading stages [9]. 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 [17] 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 [4].

Existing emission estimation methods for dredging oversimplify real-world conditions and lack adaptability to varying equipment and project characteristics. This study 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. This study advances the current state of knowledge on sustainable port maintenance dredging in several keyways. First, it introduces a physics-based, event-level emission estimation framework that explicitly links vessel components, operational activities, sediment properties, and project-specific conditions, moving beyond aggregated or empirical emission factors commonly used in literature. Second, by integrating discrete-event simulation with detailed power and energy models, the proposed method enables situation-specific quantification of trade-offs between project duration, energy consumption, and CO_2 emissions. Third, the study introduces an event-table-based approach, enabling stakeholders to zoom between detailed operational behavior and aggregated project-level performance, thereby supporting informed fleet selection and strategic decision-making in port maintenance dredging. Finally, this research provides one of the first validated, comparative emission assessments of TSHDs and WIDs within a unified modeling framework, supported by real vessel and activity logs. This allows for a transparent comparison of fundamentally different dredging strategies. The framework presented in Section 2 supports multi-perspective analysis and helps formulate the problem, and outlines some key modeling decisions. Section 3 applies this framework to analyze dredging activities, and Section 4 summarizes the findings and outlines future research directions.

2. Methodology

To systematically quantify energy use and exhaust emissions associated with alternative port maintenance dredging strategies, this study adopts an event-based modeling framework that integrates discrete-event simulation with physics-based energy and emission estimation.

The framework explicitly links project-specific conditions, vessel characteristics, and operational behavior to power demand, energy consumption, and CO_2 emissions at the level of individual dredging activities. As illustrated in Fig. 1, vessel activities and operational constraints are first represented using a discrete-event simulation, after which physics-based models are applied to estimate power and energy use for each event. These results are subsequently consolidated in an event table, enabling aggregation across spatial and temporal scales and supporting quantitative trade-off analysis between project duration and emissions. This structured approach provides a transparent and reusable basis for comparing fundamentally different dredging strategies under realistic port conditions.

2.1. Conceptual modeling of emission estimation for port maintenance dredging

In order 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 [4] 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 adopted and extended OpenCLSim 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.

$$EM_T = E_T \times SFC \times EF \tag{1}$$

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 [7,9,14]:

$$E_T = \int P_x dt \tag{2}$$

The power required for different dredging activities is allocated to pumps, propulsion systems, bow thrusters, and the vessel's onboard power network. Pump power is mostly used for fluidizing and transporting sediment, while propulsion power is needed to overcome the resistance of the vessel hull and the dredging-related appendages. Bow thruster and onboard net power are kept as constant terms for simplicity. A full breakdown of power consumption for both TSHD and WID vessels is provided in Appendix A. When estimating the project duration for WID, the distance between the dredging site and the port entrance is a critical factor To account for this, the port area can be divided into zones based on two hydrodynamic regimes: high-energy environments (HEE) near the port entrance, where strong tidal currents assist sediment dispersion, and low-energy environments (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

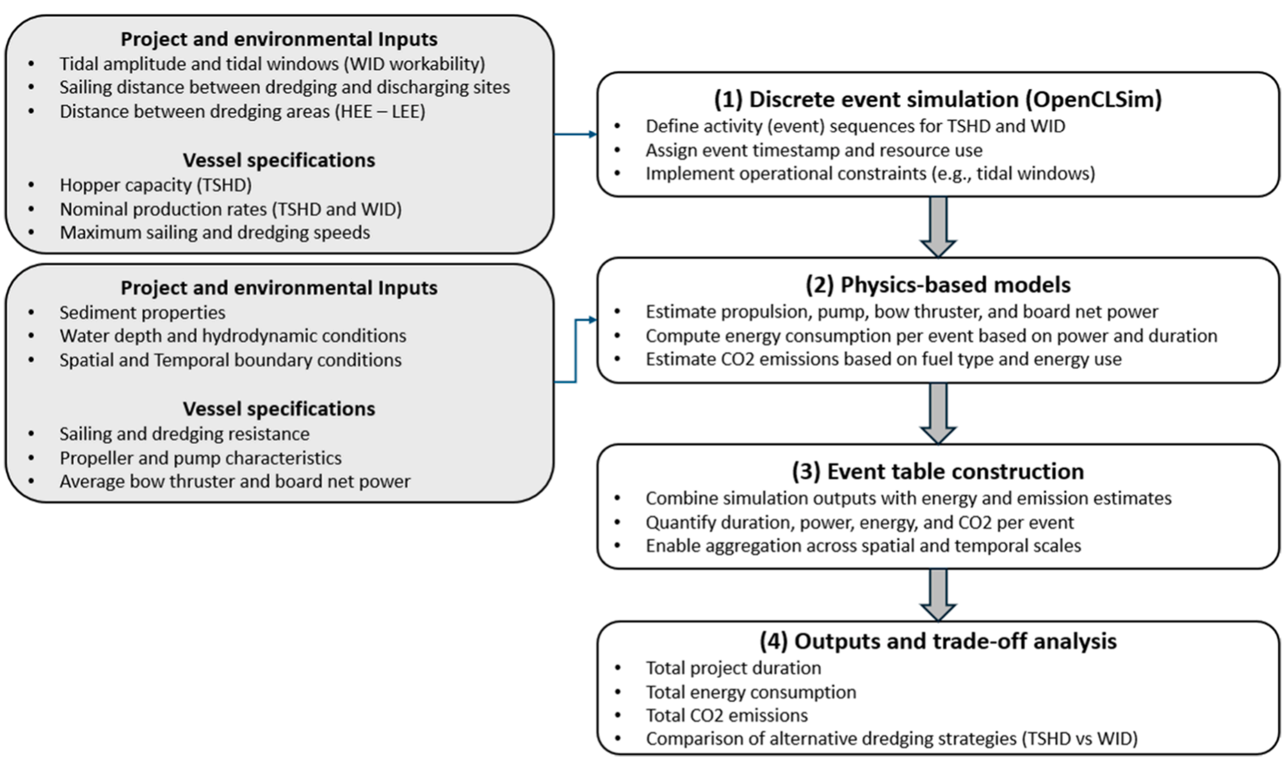


Fig. 1. Event-based emission estimation framework integrating discrete-event simulation and physics-based energy models to quantify time-emission trade-offs in port maintenance dredging.

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 [6]. More details of estimating the duration and production rates are summarized in Appendix B.

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. The data in the Appendices highlight the energy usage differences driven by vessel type and soil characteristics. 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 [27]. Finally, estimated durations and emissions for the WID are validated against vessel and activity logs to ensure accuracy.

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 [26], 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 1 presents how each perspective translates into specific data and analytical requirements for emission estimation in the context of port maintenance dredging.

Table 2 provides a more detailed description of goals for the case of port maintenance dredging, along with specified requirements for the data that is going to be incorporated in the event table.

2.3. 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 m in the entrance channel and 7 m in the berth area. We incorporate hydrographic survey data that shows a total of 135,000 m^3 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 Fig. 2a). To have a more accurate estimation of dredging productivity, the whole dredged area is divided into four

Table 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
Behavior (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 (Interdependencies 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 2
Using the perspectives to define requirements for.

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
Behavior (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

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 Fig. 2b). 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 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

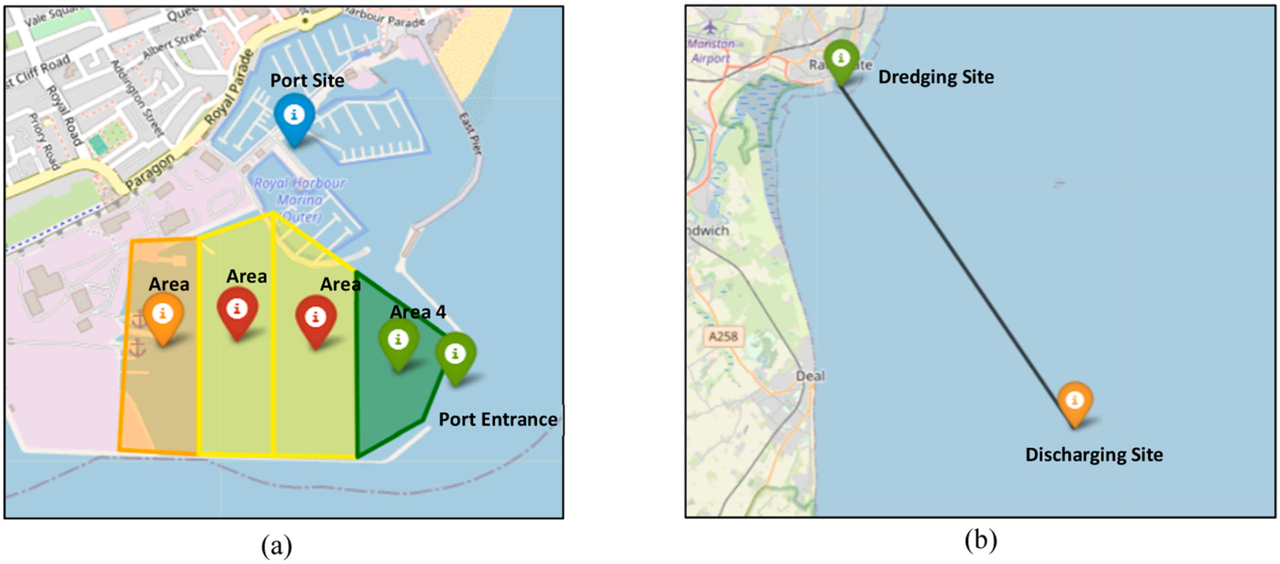


Fig. 2. Port site and dredging areas in the Port of Ramsgate (a) when using a WID; and (b) when using a TSHD (Source: OpenStreetMap).

affect this difference.

2.4. Conditions

The influencing factors on the emission estimation are categorized into project and vessel characteristics, which are used for the energy estimation modeling provided in Section 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 [3], incorporating the flow rate and pump head used to overcome the pipeline resistance (See Appendix A). 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 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.

2.5. Behavior

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 [19].

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.

2.6. 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.

$$h(t) = \frac{A}{2} \times \sin\left(\frac{2\pi t}{T} - \phi\right) \tag{3}$$

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.

$$\frac{dh(t)}{dt} = \frac{A\pi}{T} \times \cos\left(\frac{2\pi t}{T} - \phi\right) \quad (4)$$

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 [16]. It is assumed that the TSHD operates without tidal restrictions. Tidal window information can be extracted from public websites associated with the port authorities.

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 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 $tons/m^3$ with an average grain size diameter of 175 μm 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 m) 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 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 provided in Appendix A, and the total duration of each event is estimated based on the production calculations proposed in Appendix B. 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.

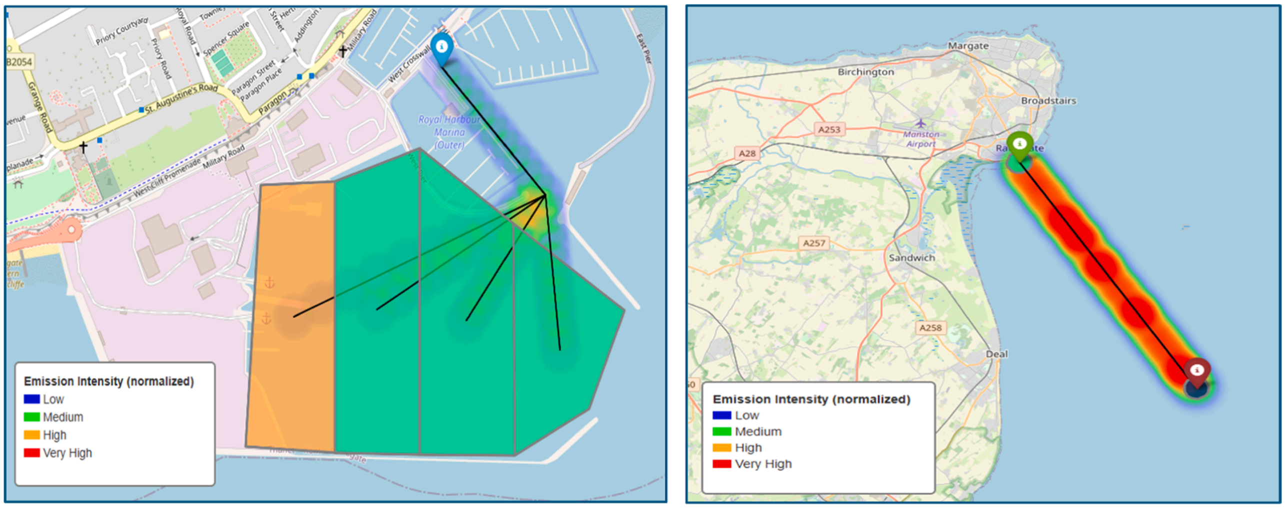
In order to show the emission distribution among different events, two separate heat maps are presented in Fig. 3, representing the intensity of emission estimates when dredging a certain area with a WID and a TSHD. In general, employing a WID contributes to considerably lower CO_2 emissions compared to the same case of using a TSHD. It is also shown that areas closer to the HEE have a less intense emission profile, as the energy needed to remobilize 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.

More detailed estimation of attributes per event is shown in Figs. 4 and 5, 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 (135,000 m^3), 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 m^3) 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 3 based on the simulations in OpenCLSim. Fig. 6 represents a comparison between these values based on tidal windows, vessel speed,

Table 3
Results of the event-based emission estimation model for activities in a single dredging cycle.

	Event ID				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]	CO_2 emission [$tons$]
1	WID 1	preparing	04:30:00	10:44:35	Port Site	-	-	-	-	20.88	20.88	130.36	0.09
2	WID 1	dredging_trip	10:44:35	11:01:52	Port Site to Area 4	25.39	-	-	53.40	20.88	99.67	28.68	0.02
3	WID 1	dredging	11:01:52	16:57:11	Area 4	154.59	766.30	-	53.40	20.88	995.18	5893.65	4.48
4	WID 1	port_trip	16:57:11	17:14:28	Area 4 to Port Site	25.39	-	-	53.40	20.88	99.67	28.68	0.02
5	TSHD 1	sailing empty	04:30:00	05:18:03	Discharging Site to Dredging Site	3475.90	-	-	44.00	182.00	3701.90	2965.17	2.54
6	TSHD 1	loading	05:18:03	05:34:57	Dredging Site	2153.62	919.52	1746.48	44.00	182.00	5045.63	1420.45	1.21
7	TSHD 1	sailing full	05:34:57	06:29:35	Dredging Site to Discharging Site	2204.60	-	-	44.00	182.00	2430.60	2213.30	1.89
8	TSHD 1	unloading	06:29:35	06:30:29	Discharging Site	0.41	919.52	-	44.00	182.00	1145.94	17.18	0.01



(a) (b)

Fig. 3. Heatmap of CO_2 emissions when using (a) a WID and (b) a TSHD.

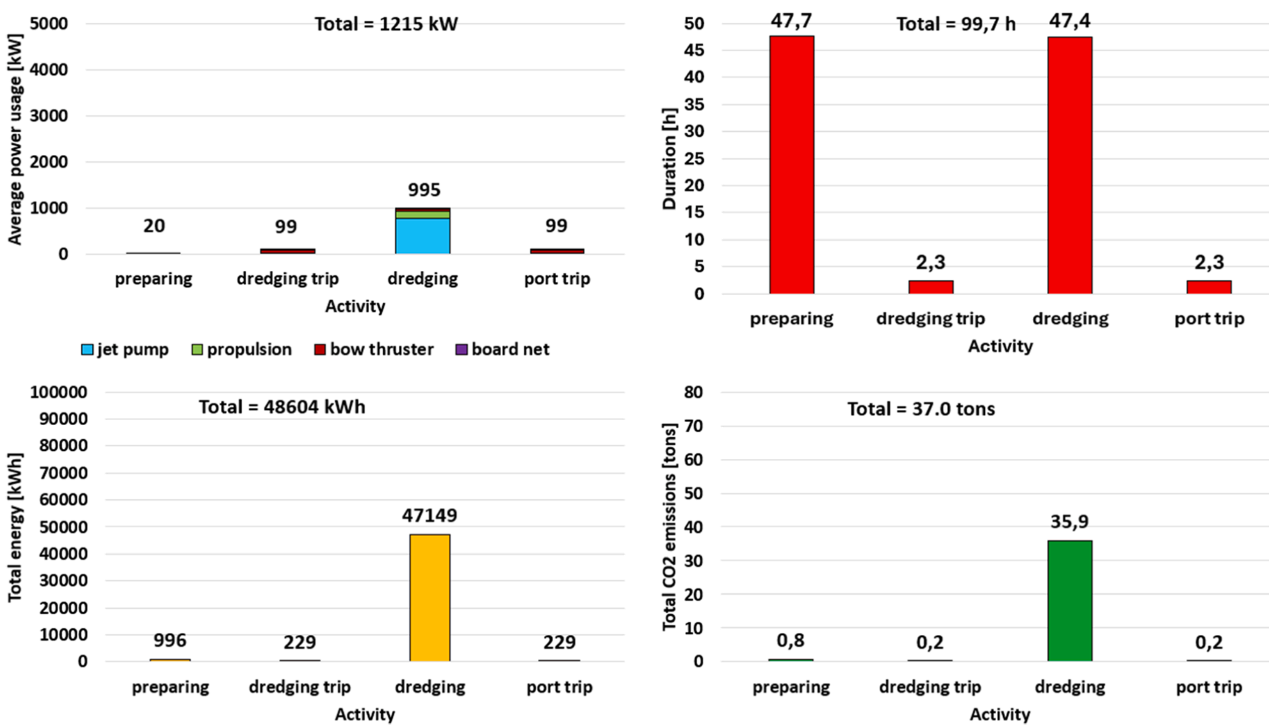


Fig. 4. Estimation of attributes per event for the WID vessel.

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. Fig. 7 summarizes 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 in 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-

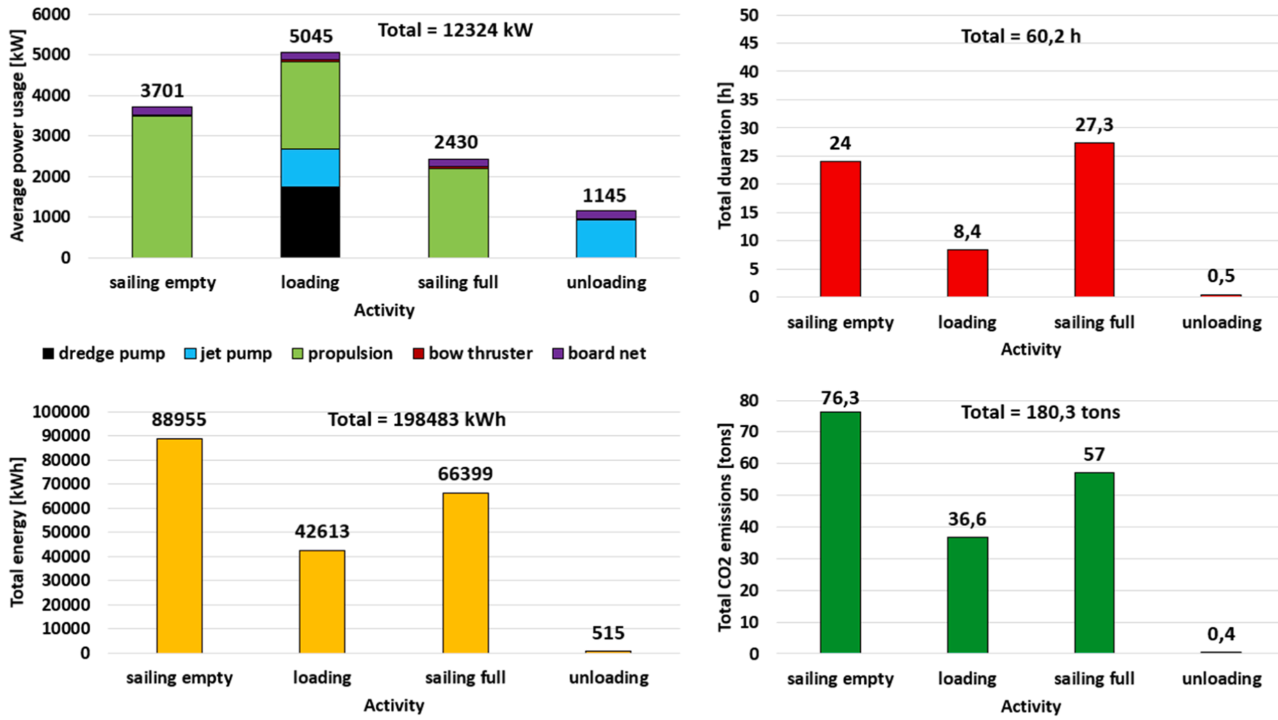


Fig. 5. Estimation of attributes per event for the TSHD vessel.

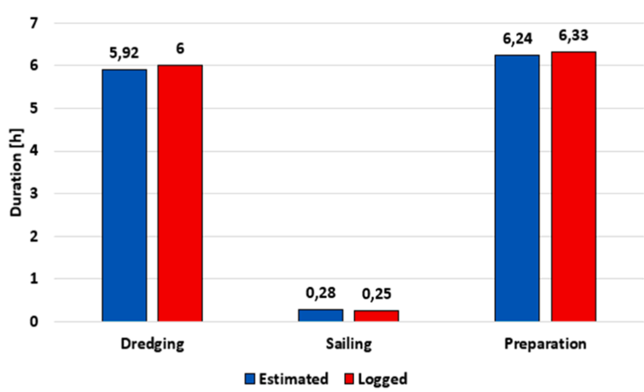


Fig. 6. Estimated versus logged activity durations for the WID.

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, 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 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.

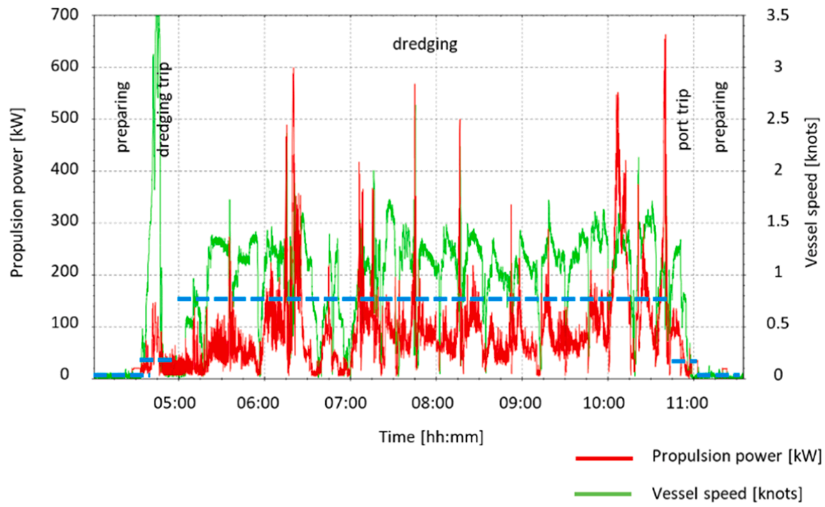
4. Discussion

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 [7] and Miedema et al [14]. 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.

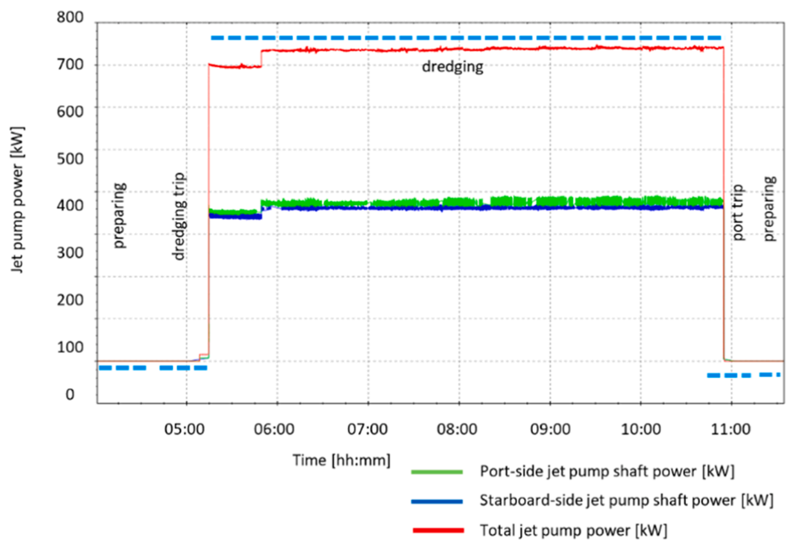
A key contribution is the quantification of trade-offs between time and CO_2 emissions across three dredging strategies. TSHDs generally achieve higher production rates and are less constrained by tidal windows, enabling shorter project durations. However, TSHDs exhibit substantially higher energy consumption 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.

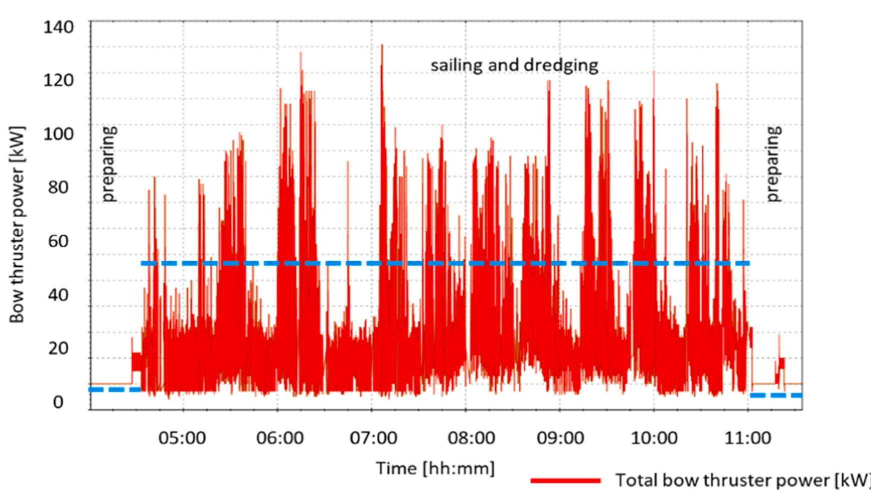
The study focuses on only two dredging vessel types (TSHDs and WIDs), excluding other relevant equipment like plows, backhoes, and grab dredgers, which could also be viable depending on availability and



(a) Logged propulsion power [kW] (estimated values for preparing: 0, dredging and port trips: 25.39, and dredging: 154.59)



(b) Logged jet pump power [kW] (estimated values for preparing: 0, dredging and port trips: 0, and dredging: 766.30)



(c) Logged bow thruster power [kW] (estimated values for preparing: 0, dredging and port trips: 53.40, and dredging: 53.40)

Fig. 7. Comparison between estimated and logged values of power consumption. (a) Logged propulsion power [kW] (estimated values for preparing: 0, dredging and port trips: 25.39, and dredging: 154.59). (b) Logged jet pump power [kW] (estimated values for preparing: 0, dredging and port trips: 0, and dredging: 766.30). (c) Logged bow thruster power [kW] (estimated values for preparing: 0, dredging and port trips: 53.40, and dredging: 53.40).

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.

5. Conclusion

This study contributes a novel, integrative framework for estimating emissions and evaluating alternative maintenance dredging strategies, grounded in both physics-based modelling 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 favourable 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.

CRediT authorship contribution statement

Arash Sepehri: Writing – original draft, Visualization, Validation, Methodology, Formal analysis, Data curation, Conceptualization. **Alex Kirichek:** Writing – review & editing, Validation, Supervision, Data curation. **Marcel van den Heuvel:** Writing – review & editing, Supervision, Funding acquisition. **Martin de Geus:** Writing – review & editing, Validation. **Mark van Koningsveld:** Writing – review & editing, Validation, Supervision, Software, Data curation.

Declaration of competing interest

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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Appendix A

Total power consumption for TSHD and WID operations is estimated using a combination of physics-based models, literature, and empirical data. Table A.1 summarizes the active energy consumers for each activity phase.

Table A.1
Active energy consumers per activity in a TSHD and a WID.

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

A detailed breakdown of the power consumption terms is provided as follows.

Propulsion power

Propellers provide a vessel with the maneuverability and power required for sailing, dredging, and transporting sediment. Diesel engines in a TSHD are used to provide the primary power source for these activities, while a WID also relies on seabed natural currents and tidal conditions for sediment re-mobilization. Vessel's propulsion power $P_{propulsion}$ per activity is calculated based on the total resistance R_{total} posed to the vessel, the vessel's speed v required to overcome the resistance, and the total efficiency η_{total} affecting the vessel while doing each activity.

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

The total resistance R_{total} is calculated by aggregating friction resistance, wave resistance, pressure resistance, and residual resistance while doing all of the activities. Vessels are affected by an additional resistance term due to dredging appendages while conducting dredging [7,9,13,17,21]. Total efficiency η_{total} is the product of several component efficiencies, including open water, hull, shaft, and gearing efficiencies that affect the vessel based on the activity it performs [22].

Pump power

Dredging pumps and jet pumps are used to fluidize the material and facilitate the suction process during the loading phase or remobilization process when conducting low-pressure injection to the sediment bed. To have an accurate estimate of pump power consumption, the pump working point is a determining factor, which is the point where the pump's flow rate Q (pump moves per unit of time) and total head H_T (the height where the pump can lift or pressurize the fluid) meet the system's demand and overcome pipeline resistance while dredging [3]. Total pump power also incorporates gravitational acceleration g, slurry density ρ, and pump efficiency η_{pump}.

$$P_{pump} = \frac{\rho \times g \times Q \times H_T}{\eta_{pump}} \tag{A.2}$$

If head loss increases due to changes in pipeline resistance (such as modifications to the pipeline design or the nature of the mixture being pumped), it may be necessary to select a different pump or adjust operating conditions (e.g., speed, impeller diameter) to achieve the desired flow rate and head [23]. The pump head (H_T) represents the energy per unit weight of the fluid required to move it through the entire system, from the pump inlet to the outlet.

$$H_T = H_{static} + H_{vacuum} + H_{additional} + H_{loss} \tag{A.3}$$

It is assumed that static, vacuum, and additional losses are calculated based on the empirical knowledge of different pumps, while the head loss is calculated using the Darcy-Weisbach equation.

Bow thrusters and board net power

Bow thrusters are transversal propulsion devices installed in the bow of a vessel to provide lateral movement. They are primarily used for maneuvering, especially in ports or tight areas, without relying on the main propulsion system. Board net power refers to the electrical power consumption of onboard systems, excluding the main propulsion and dredging pumps. In this study, a power factor is multiplied by the total power installed for bow thrusters and board net to estimate the final consumption term. Power coefficients α are based on operational data.

$$P_{bow.thruster} = \alpha_{bow.thruster} \times p_{ins.bow.thruster} \tag{A.4}$$

$$P_{board.net} = \alpha_{board.net} \times p_{ins.board.net} \tag{A.5}$$

Appendix B

This appendix outlines how activity durations and production rates are estimated, forming the basis for total energy consumption and emission assessments. To estimate the sailing duration of each activity, a simple equation of dividing the sailing distance d by the vessel's speed v is used in this study $(t = d/v)$. Assuming that the sailing between two locations follows a linear route, multiple points along a path can be used to estimate the total sailing distance while an average sailing speed is adopted.

Total loading duration (in s) of a TSHD is calculated considering the total hopper capacity of the vessel V_{hopper} (in m^3) and the vessel's excavation production rate $Q_{excavation}$ (in m^3/s), while the total unloading duration of the vessel follows a constant unloading rate when bottom door discharging is used $C_{unloading}$.

$$t_{loading.tshd} = \frac{V_{hopper}}{Q_{excavation.tshd}} \tag{B.1}$$

$$t_{unloading.tshd} = \frac{V_{hopper}}{C_{unloading}} \tag{B.2}$$

As a WID works continuously, the vessel stops dredging only when tidal conditions are not favorable. Tidal amplitude t_{tidal} shows the duration of a full tidal cycle, and the WID vessel conducts dredging during the outgoing tide (half the duration of a tidal window) when the fluidized sediment is remobilized by natural currents and tide.

$$t_{dredging.wid} = \frac{t_{tidal}}{2} - t_{sailing.wid} \tag{B.3}$$

Total excavation production of a TSHD is an aggregate of jet production for material loosening [28,29], cut production for the cutting and sucking the material into the hopper bin [5,21], and erosion production. Assuming that overflow is not allowed in this case, each production term includes various parameters such as sediment properties, penetration depth of the cutting teeth and jet nozzles, and mass flux.

Total excavation production of a WID is estimated based on the performance of the jetting process in penetrating the sediment bed and the area production, which is based on the vessel's speed and the area being injected using a jet bar with a certain width [15]. Moreover, sediment type, distance between HEE and LEE, and tidal amplitude play an important role in restricting the production rate of the vessel when working on a project [17].

Data availability

The data that has been used is confidential.

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