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Sustainable Hull maintenance strategies in Baltic Sea region through case studies of RoPax vessels

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ABSTRACT

Determining optimal maintenance strategies in unique maritime environments like the Baltic Sea is challenging, as it should consider various aspects, including ship characteristics and environmental conditions. This study employs the decision support tool HullMASTER (Hull MAintenance STrategies for Emission Reduction) to assess the life cycle costs of different hull maintenance scenarios for RoPax vessels in the Baltic Sea. Findings indicate that optimal hull management can save operators up to €9.3 million and reduce socio-environmental damage costs by €7.9 million over ten years compared to a less proactive baseline. Notably, biofouling pressure decreases from the high-salinity Skagerrak and Kattegat to the low-salinity Baltic Proper, emphasizing the need for tailored maintenance strategies. Among the coatings analyzed, non-biocide foul-release coatings are the most sustainable choice, reducing emissions to the ocean and the atmosphere. These findings will provide practical guidelines for sustainable hull management strategies, contributing to enhanced operational efficiency and marine environmental protection.

1. Introduction

Biofouling refers to the accumulation and growth of marine organisms on underwater structures and surfaces and it significantly affects the performance of marine infrastructure and technical equipment (Davidson et al., 2009; Weber and Esmaeili, 2023). For ships, biofouling on the hull surface results in increased drag, necessitating additional shaft power to maintain operational performance (Schultz, 2007). This leads to an increase in fuel consumption, thereby escalating the environmental footprint of the maritime industry through heightened greenhouse gas emissions, as well as particulate matter, nitrogen oxides (NOx), and sulfur oxides (SOx). These emissions contribute to broader environmental issues such as marine eutrophication, and acidification of oceans and freshwater bodies, and have adverse effects on human health due to air quality degradation (Hadžić et al., 2022). Specifically, the Baltic Sea is heavily affected by this eutrophication and the inputs of chemicals, resulting in a poor environmental status and a major threat to biodiversity (HELCOM, 2023a). Consequently, efficient biofouling management is identified as a critical task in ship operations and a significant issue within the global maritime industry (Liu et al., 2023).

The primary management strategy to control or prevent the undesired attachment of marine organisms to a ship's hull involves the use of antifouling coatings, which are typically applied during the construction of new vessels or dry-docking. Moreover, the current strategy also includes the physical removal of marine life from the hull during in-water cleaning (Hopkins et al., 2021). However, the majority of traditional antifouling coatings contain biocides, such as cuprous oxide, which are released upon contact with seawater (Lindholdt et al., 2015). Recent studies have indicated that copper-based antifouling paints contribute to a third of the total copper load entering the Baltic Sea (Ytreberg et al., 2022). Additionally, the release of toxic substances from these paints and increased exhaust gas emissions poses serious socio-environmental implications, including damage to human health and marine ecosystems (Ytreberg et al., 2021). As an alternative, the use of biocide-free silicone foul-release coatings is increasing (Lejars et al., 2012; Hu et al., 2020). Ecotoxicological studies, albeit few, show that foul-release coatings are substantially less toxic to marine organisms as compared to conventional copper-based coatings (Lagerström et al., 2022). In addition, biofouling efficacy tests conducted in the Baltic Sea region have shown foul-release coatings to perform as well as or better than copper-based coatings (Oliveira and Granhag, 2020; Lagerström et al., 2022).

The process of determining the optimal hull maintenance strategy is complex, influenced by variables such as the ship's size, operation patterns, navigation areas, and voyage schedule (Kim et al., 2022).

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Furthermore, formation and development of biofouling on ship hulls vary according to environmental factors such as temperature, salinity, light, pH, nutrient richness, and water flow velocity, leading to different fouling pressures in various regions (Uzun et al., 2019; Wrange et al., 2020; Darvehei et al., 2018; Brown et al., 2018; Lehaitre et al., 2008; Radu et al., 2012; Hellio and Yebra, 2009). In addition, the leaching rate of copper from antifouling coatings has been shown to be governed by the ambient waters' salinity and temperature (Valkirs et al., 2003; Lagerström et al., 2018), implying that the efficacy of copper-based coatings to prevent biofouling may be lower in low temperature and low saline waters. Hence, applying biofouling management methods from full marine regions with fairly high winter temperatures, e.g. the Mediterranean, to areas with unique marine environments with low-saline brackish water and partial ice cover during winter, such as the Baltic Sea, may pose challenges (Korpinen et al., 2012). The Baltic Sea, in particular, with its lateral salinity gradient across its entire surface due to the influx of high-salinity seawater through the Skagerrak and Kattegat areas, results in low salinity in the Baltic proper region (Lehmann et al., 2022). Additionally, this region possesses unique environmental characteristics, such as some areas being covered with ice during the winter and sensitive marine environments with high human intervention, including maritime traffic (IMO, 2014). In this context, ship owners need to consider not only the additional operating costs due to biofouling and hull management strategies but also the impact on climate change, human health, and the marine environment for sustainable shipping. To address these issues, a life cycle cost analysis is needed to evaluate the economic, social, and environmental impacts of various measures over their entire life cycle and integrate different evaluation criteria to derive the optimal decision (Mondello et al., 2023).

There have been various studies conducted on models evaluating the economic and environmental impacts of different factors considered in hull biofouling management. Dinariyana et al. (2022) developed a decision support system based on an iterative model to predict the optimal hull cleaning timing, considering the balance between the degradation in ship performance and the maintenance cost due to biofouling. The system includes estimates of ship resistance, additional resistance due to biofouling, and identification of the most suitable timing for hull cleaning. However, it has limitations in generalization as it is only applicable to specific scenarios or data inputs. Kim et al. (2022) analyzed the relationship between changes in ship performance based on computational fluid dynamics (CFD) simulations following dry docking and in-water hull cleaning (IWHC). Accordingly, they provided guidelines for efficient hull management. However, this approach requires individualized evaluation, as each vessel has different design characteristics. Degiuli et al. (2023) evaluated performance degradation due to biofouling through the cases of Post Panamax and Post Panamax Plus container ships operating in the Adriatic Sea and proposed a comprehensive model for an appropriate cleaning schedule considering hull cleaning costs. However, their cost evaluation did not account for variations in cleaning costs related to the ship's wetted surface area, seasonal factors, and market conditions due to insufficient data.

On the other hand, Wang et al. (2018) implemented a life cycle model to ascertain the optimal hull management plan for a short-route hybrid ferry, taking into account both economic and environmental implications. Pagoropoulos et al. (2018) quantitatively evaluated the economic and environmental impacts of the frequency of IWHC for managing biofouling on oil tankers using temporally and spatially distributed models. However, uncertainties may arise from the consideration of various ship activities that were either not addressed or partially addressed within the life cycle. Luoma et al. (2022) developed a multi-criteria decision analysis model to probabilistically compare biofouling management strategies in the Baltic Sea. They incorporated Bayesian networks to estimate comprehensive environmental impacts and monetary costs, considering the ship's characteristics, operational profiles, and operating environments. Oliveira et al. (2022) introduced HullMASTER (Hull MAintenance STrategies for Emission Reduction), a tool designed to enable various stakeholders in the maritime industry to assess the economic and environmental costs of ship hull maintenance strategies and facilitate decision-making. These life cycle assessment (LCA)-based studies have the characteristic that their results can vary significantly depending on the availability and accuracy of the data, as they are based on many assumptions and diverse input data. In addition, multi-criteria decision analysis requires careful interpretation of results based on the criteria used.

Numerous studies have predominantly concentrated on the operational costs associated with biofouling and its management. While some studies have performed comprehensive analyses of the economic and environmental damage costs related to biofouling, the majority were confined to specific case scenarios. Notably, there has been a lack of research utilizing life cycle cost analysis tools to determine the most sustainable hull management strategy by simulating an extensive range of hull management scenarios on Baltic Sea routes. In this paper, as a continuation of Oliveira et al. (2022), we employ HullMASTER to simulate various hull management scenarios in the Baltic Sea region and conduct a cost-benefit analysis from the operator and socio-environmental perspectives. While the previous study focused on the background, module composition, and validation of HullMASTER, which provided a foundation for the economic, social, and environmental assessments related to hull maintenance, this study evaluates actual cases based on four navigation routes of RoPax vessels in the Baltic Sea region, including the Skagerrak, Kattegat, and Baltic Proper areas. This analysis aims to assess the impacts of hull management on economic, social, and environmental aspects and to identify the most sustainable hull management strategies for these vessels.

According to HELCOM (2023b), RoPax ships are responsible for a substantial portion of transportation and trade in the Baltic Sea, accounting for 24 % of the total CO_2 emissions from maritime activities in the area. This highlights the urgency of adopting sustainable hull maintenance strategies for these ships. Through the life cycle cost analysis of such ship cases, we examine the correlation between the characteristics of hull management and operational areas within the Baltic Sea region. Furthermore, this paper aims to provide valuable insights into an overall sustainable hull management strategy that not only contributes to societal and environmental protection but also minimizes operational costs for shipowners.

2. Methodology

2.1. HullMASTER: decision support tool

In this study, we employ HullMASTER, a decision-support tool for hull surface maintenance strategies to conduct a detailed comparison of costs and benefits across a range of scenarios for a given ship in the Baltic Sea. As described by Oliveira et al. (2022), this tool was developed based on data such as biofouling growth on different coating types and the release rate of biocides from antifouling coatings performed in the Baltic Sea and adjacent port areas. It enables an analysis of the operator's costs and socio-environmental impacts resulting from various hull maintenance scenarios tailored to a specific ship and operational profile.

The validation of this tool was achieved using measured data from 9 vessels operating in the Baltic Sea region, representing approximately 40 cumulative years of operation. The propulsion penalty caused by biofouling and hull maintenance, as estimated by HullMASTER, showed a relatively low error, with an average deviation of -3.2 ± 3.8 % from the ship's measurement. While HullMASTER has potential applications in other regions with environments similar to that of the Baltic Sea, further examination is needed to determine its universal applicability. HullMASTER and its underlying assumptions have been described in detail by Oliveira et al. (2022). During this study, some improvements were made to the tool. Here, we present a brief overview of HullMASTER along with the modifications and updated assumptions made.

2.1.1. Hull fouling growth model

The rate of biofouling establishment and growth on the hull surface is determined by various parameters. In particular, cumulative idle time (Oliveira and Granhag, 2020) and salinity (Wrange et al., 2020) were found to be the two most important variables for predicting fouling growth rates in the Baltic Sea region. The fouling growth model of HullMASTER was established based on obtained data from static immersion tests of coated panels conducted at three different locations along the Swedish coast: Askö (6 practical salinity units, psu), Kristinberg (24 psu), and Tjärnö (26 psu) (Lagerström et al., 2022). The field tests were conducted over approximately 8 to 12 months depending on location, and different types of coatings were investigated, including copper-based antifouling coating, biocide-free foul-release coating, and inert abrasion-resistant coating. Salinity measurement data was collected at a depth of 1 m at the monitoring sites in Askö and Tjärnö or a nearby buoy in Kristineberg. This data was compiled on a monthly basis and averaged annually to represent the typical salinity at each location. Based on the photos taken almost monthly, the type and surface area of fouling organisms on the panels were assessed and then used to calculate the cumulative time. The hull fouling condition is defined based on the frNSTM fouling grade of the U.S. Navy (Navy, 2006), and the mean fouling rating of the visually observed panels can be calculated by using Eq. (1). The cumulative fouling degree over time is obtained by fitting these observed data using a Gaussian curve (Uzun et al., 2019) as shown in Eq. (2).

$$fr_{NSTM,obs} = mean\left(\sum_{i=1}^{l}\frac{fr_{NSTM,i}\times(\%cover)_i}{100}\right) \tag{1}$$

$$fr_{NSTM,fit}(t_{idle}) = a\times e^{-\left(\frac{t_{idle}-b}{c}\right)^2} \tag{2}$$

Here, t_{idle} represents cumulative idle time in water (days), l is the total number of fouling rating types observed on the panel, $fr_{NSTM,i}$ is the i-th fouling rating based on US Naval Ships' Technical Manual fouling rating, $(\%cover)_i$ is the percentage of the i-th fouling rating covering the panel, $fr_{NSTM,obs}$ is the mean fouling rating of visually observed panel, a, b, and c are coefficients where observed mean fouling rating is fitted to the Gaussian curve, and $fr_{NSTM,fit}$ is the Gaussian fitted mean fouling rating from observed samples.

Fig. 1a depicts NSTM fouling rating growth curves of different coating types according to the ship's cumulative idle time used in the HullMASTER. The graphs in the figure cover various salinity levels, including those of the port of call of the ships to be analyzed in this study. These curves are Gaussian-fitted based on the mean value of the data obtained from the static immersion tests of coated panels conducted over approximately one year, with subsequent periods extrapolated. Fig. 1b shows the fouling growth curves of the hull applying copper-based antifouling coating at 22 psu as an example according to the ship's idle ratio. Here, a ship's idle time refers to periods when the ship is stationary, such as when berthed at port or anchored, and the idle ratio indicates the proportion of idle time to the total operation time. In consideration of the customary drydocking interval of RoPax vessels, the graph is presented for a maximum of 3.5 years during the vessel's operation time, as will be elaborated upon subsequently.

As shown in Fig. 1a, regardless of the coating type, fouling growth is faster in areas with higher salinity. Copper coatings and foul-release coatings demonstrate almost similar antifouling efficacy in all the salinity range analyzed for about a year. For inert coatings, antifouling efficacy is significantly lower compared to the other two coatings. Additionally, in areas with higher salinity, where fouling intensity is stronger, the antifouling effects of copper coatings and foul-release coatings are more pronounced. However, it is important to note that antifouling efficacy may be affected by various environmental conditions such as temperature, pH, nutrient levels, and flow speeds, and the trend in coating efficacy beyond the field test period is subject to high uncertainty.

The antifouling efficacy of these coatings can vary depending on the ship's operational profile, such as idle time versus the ship's operating time, as shown in Fig. 1b. It is common for marine organisms to adhere to and proliferate on the ship's hull surface during these idle periods, with longer idle times providing more opportunity for such growth. That is, depending on the vessel's operational profile, hull roughness conditions can vary greatly, and biofouling typically commences slowly but escalates exponentially over time. However, despite this growth trend, the fouling of marine organisms usually does not continue indefinitely due to the regular implementation of various hull maintenance actions on ships.

2.1.2. Energy penalty associated with increased hull roughness

As a ship's operation time increases, hull fouling gradually accumulates, which leads to propulsive penalties associated with increased

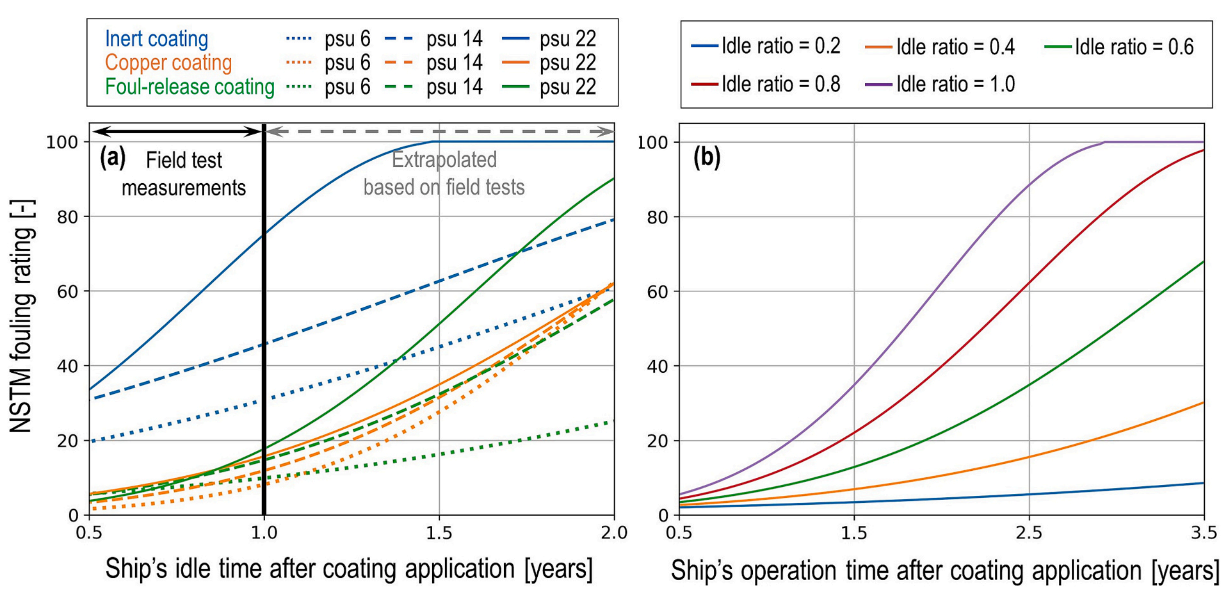


Fig. 1. (a) NSTM Fouling rating according to salinity by coating type and (b) NSTM Fouling rating according to idle ratio of copper coating at 22 psu. NSTM fouling ratings in excess of one year are extrapolated based on the curve fit of the field test measurements.

hull roughness. The hull surface condition with fouling is translated into an estimate of the equivalent sand roughness height (k_s) using a fitting curve proposed by Schultz (2007) in Eq. (3). The increase in towing resistance, a consequence of hull roughness, can be calculated in kilonewtons (*kN*) using Granville's method (Granville, 1987), also known as the flat plate similarity law scaling method. Finally, this methodology enables us to estimate the power penalty of the vessel resulting from hull fouling, under the assumption that the impact on propulsive efficiency is negligible, as shown in Eq. (4). Furthermore, environmental burdens due to propulsion penalties from hull fouling, such as greenhouse gas emissions, are calculated based on emission coefficients. Emission coefficients can be categorized into energy-based (*kg/kWh*) or fuel-based (*kg/kg of fuel*), and detailed explanations can be found in the International Maritime Organization's (IMO) 4th Greenhouse Gas (GHG) Study (IMO, 2020b) and Oliveira et al. (2022).

$$k_s(t) = 46.927 \times e^{0.056614 \times fr_{NSTM}(t)} \tag{3}$$

$$\Delta P(t) = \frac{\Delta R(k_s(t)) \times V}{\eta_D} \tag{4}$$

Here, $k_s(t)$ represents the equivalent sand roughness height (μm) due to biofouling at cumulative idle time t (days), ΔP is the power penalty due to hull fouling (kW), ΔR is the increase in resistance due to hull fouling (kN), V is the speed of the vessel (m/s), and η_D stands for propulsive efficiency.

2.1.3. Emissions from the antifouling coating

Commercial antifouling paints on ships typically include biocides such as cuprous oxide to prevent marine fouling, which are released when the painted hull is in contact with seawater (Ytreberg et al., 2022). The coatings also include zinc oxide to control the erosion rate of the coating (Lindgren et al., 2018). The release of these toxic substances into the seawater, influenced by factors such as coating type, immersion time, cleaning type, and local salinity, is modeled based on the average release rate in the Baltic Sea region (Lagerström et al., 2020). As shown in Eq. (5), release rates denote the amount of heavy metals leached per unit wetted surface area per day.

These harmful substances are primarily released naturally when the coated hull comes into contact with seawater, with additional amounts emitted during hull maintenance activities such as IWHC. The passive release rate underwater is determined based on the data from Lagerström et al. (2020), applying a consistent decay ratio to the release rate proposed by Valkirs et al. (2003) to explain its long-term discharge. The additional amount of copper (Cu) and zinc (Zn) that can be released during or after hull cleaning events is estimated based on the weight content of the biocide in the removed coating thickness (Tribou and Swain, 2017). The release of Cu and Zn by relatively gentle hull cleaning (low and medium intensity IWHC) were modified in this study and based on recent effluent data from IWHC by divers presented in Soon et al. (2021), where effluents are assumed for the low and high emission scenarios of Granhag et al. (2023) (Cu: 3.46–248, Zn: 4.95–201 $\mu g/cm^2/event$). In contrast, aggressive cleaning methods (high intensity IWHC) that cause higher levels of abrasion are calculated based on paint removal values from Morrisey et al. (2013) (*75 μm/event*). The increased passive release rate after hull cleaning events is modeled, as previously, based on Earley et al. (2014).

$$Total\ Cu\ (or\ Zn)\ emissions = S \times \sum_{j=1}^{m} \left[RR_{t_j} \left(t_j - t_{j-1} \right) \right] \tag{5}$$

Here, S represents the hull wetted surface area (m^2), RR_{t_j} is the release rate of the toxic substance (Cu or Zn) at time step t_j ($kg/m^2/day$), m is the total cumulative idle time (the number of simulation points), and j is the time step index (days).

2.1.4. Operator and socio-environmental cost assessment

The impacts and costs related to hull fouling and management in HullMASTER are categorized into two groups: operator costs and socio-environmental costs. The operator's costs consist of bunker penalties, hull maintenance activities, and finally paint and application costs. The bunker penalty refers to the additional cost resulting from the increased propulsion power when sailing with a fouled hull compared to a hydraulically smooth one. Coating maintenance costs include expenses for in-water hull washing, grit-blast cleaning, and full/partial paint application. However, other dry-docking costs, such as inspection costs, dock rental, and revenue loss due to vessel off-hire, are excluded from this category.

On the other hand, beyond the operator's costs, socio-environmental damage costs are considered externalities, which are expenses not directly shouldered by shipowners, charterers, or operators. There are emission-related damage costs from a fouled hull, which include human health, climate change, and marine eutrophication. Moreover, the expenses related to marine ecotoxicity also take into account the effects from the emissions of Cu and Zn from antifouling coatings and any discharge of PAH (Polycyclic aromatic hydrocarbon) and metals in scrubber water on the marine environment (the latter is only applicable under scenarios that a vessel is using high sulfur heavy fuel oils (HFOs), e.g. IFO380 with an open loop scrubber). Details on the categories and sources of these costs are provided in *Supplementary materials: Assumption used in HullMASTER*, and information related to bunker prices can also be found in *Supplementary materials: Price volatility by time of year and fuel type*.

The operator costs and socio-environmental costs arising from a ship's propulsion penalty due to biofouling are calculated as the relative cost of the change in comparison to a hydraulically smooth hull condition. However, other costs such as coating application, maintenance, IWHC, and damage to marine ecosystems are based on absolute costs. Therefore, it should be noted that the costs modeled by HullMASTER do not represent the absolute (true) costs incurred in the operation of a ship. Hence, the tool is currently optimized to only be utilized for comparing life cycle cost analysis results between a baseline and a specific scenario, thereby evaluating the effectiveness of a given practice through the relative cost differences.

2.2. Case studies

2.2.1. Study area

Due to the influx of high-salinity seawater through the Skagerrak and Kattegat regions, a salinity gradient is formed across the entire surface of the Baltic Sea. Overall, the Baltic Sea, as a brackish water body where freshwater and seawater mix, has lower salinity compared to seas such as the North Sea or the Mediterranean (Lehmann et al., 2022). Additionally, some parts of the Baltic Sea freeze over during winter. These changes pose challenges for the ecosystem, weakening its ability to withstand disturbances (Tomczak et al., 2013). Furthermore, due to high human intervention, including maritime traffic, IMO has designated the Baltic Sea region as a particularly sensitive sea area (PSSA) to protect it (IMO, 2014).

2.2.2. Ship navigation routes and operational profiles

In 2022, 24 % of the total CO_2 emissions from maritime activities in the Baltic Sea were attributed to Ro-Ro/Passenger (RoPax) vessels, representing the largest share among ship types. This indicates a 3.5 % increase compared to 2021, highlighting the significant impact of RoPax ships on the environmental health of the Baltic Sea region (HELCOM, 2023b). In this context, as illustrated in Fig. 2, this study aims to explore sustainable hull maintenance strategies based on the actual operational profiles of RoPax vessels operating in the Baltic Sea. To minimize variations in analysis results due to the design characteristics of ships, specific vessel specifications presented in Table 1 are selected as a representative case.

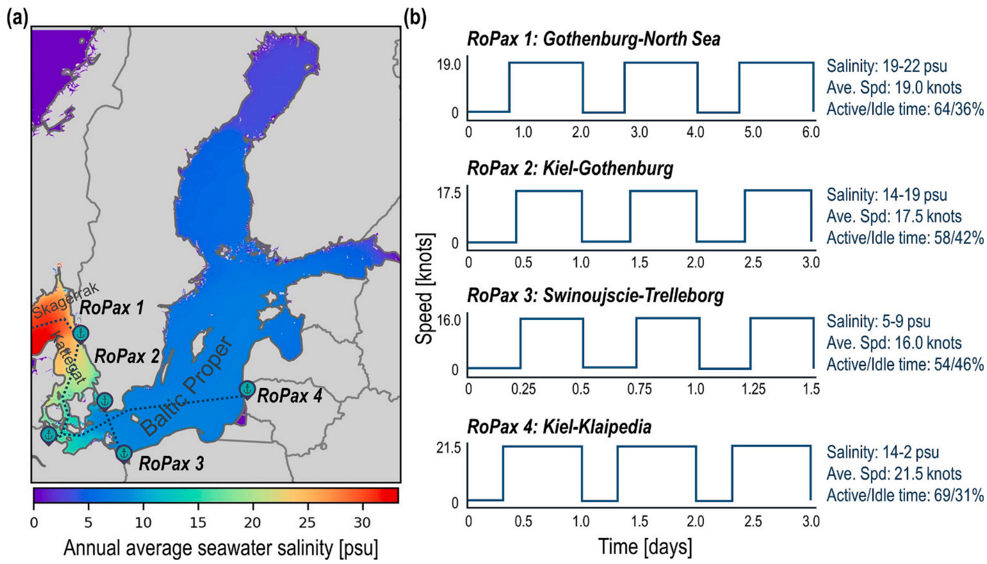


Fig. 2. (a) Operation routes and average annual seawater salinity distribution in the Baltic region used in this study (CMEMS, 2023) and (b) Ship operation profiles and seawater conditions in the corresponding routes.

Table 1
In-going ship parameters for the modelling of costs in HullMASTER.

Ship type	Length/ Beam/ Draught	Main Engine Power/ RPM	Gross/ Deadweight tonnage	Wetted surface area	Fuel type
RoPax	189.7/ 26.5/7.4 (*m*)	20,070 (kW) /123 (rpm)	32,523/10,407 (tons)	5100 (m^2)	LSMGO (0.07 % Sulfur)

The navigation area of the RoPax vessels considered in this study covers a range of different fouling pressures, caused by the salinity gradient in the Baltic Sea region, yet still allows normal ship operations throughout the year, such as ice-free or shallow ice concentration areas (Lensu and Goerlandt, 2019). Specifically, a total of four routes are considered: Gothenburg-North Sea (RoPax 1), Kiel-Gothenburg (RoPax 2), Swinoujscie-Trelleborg (RoPax 3), and Kiel-Klaipedia (RoPax 4). Moreover, it is assumed that if the ship's route extends beyond the Baltic Sea region, its point of departure is located at the boundary of the Baltic region.

The use of low-sulfur marine gas oil (LSMGO) was assumed for all scenarios as this fuel type is the most commonly used by RoPax vessels in the Baltic Sea (HELCOM, 2023b). This is due to the sulfur emission control area (SECA) regulations implemented by the IMO, which apply to the Baltic Sea and adjacent port areas, limiting the sulfur content in marine fuels to a maximum of 0.10 %.

2.2.3. Scenarios for hull maintenance

This study analyzes a total of 93 different hull maintenance scenarios, taking into account variables including coating type, dry-docking interval, and the intensity and frequency of IWHC, as detailed in Fig. 3. Here, it is assumed that the vessel sails for 10 years under the navigation route and operational profile specified in paragraph 2.2.2, while implementing the hull maintenance strategy for each scenario.

The scenarios include the three categories of coating types typically used in commercial vessels in the Baltic Sea, specifically copper-based antifouling coatings, non-biocide foul-release coatings, and inert abrasion-resistant coatings (Luoma et al., 2021). Across all scenarios, the

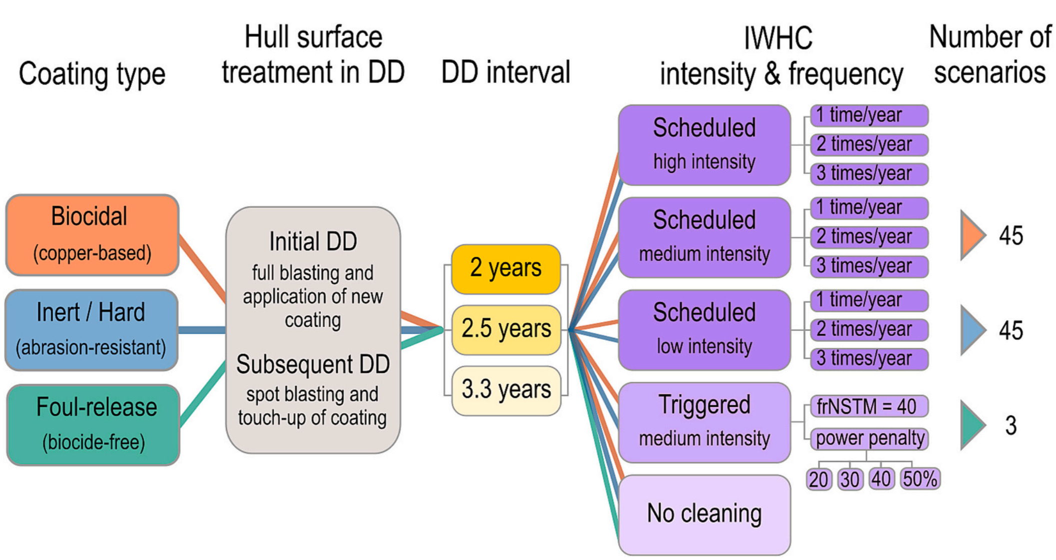


Fig. 3. Total of 93 hull maintenance scenarios used in the study. It is assumed that each vessel operates under the specified scenario for 10 years.

initial hull surface condition is presumed to be fully sandblasted and newly coated in drydock. Throughout the 10-year operation scenario, spot blast treatments and touch-up coatings will be applied at subsequent dry docks according to the specified intervals. Here, the touch-up coating is defined as a partial sandblasting treatment on 5–10 % of the wetted hull surface, which corresponds to the complete recoating of the copper biocidal paint, patch painting of foul-release and inert coating types (Gundermann and Dirksen, 2016). Furthermore, dry-docking intervals of 2, 2.5, and 3.3 years are considered in the scenario since for passenger ships, the ship's bottom needs to be inspected annually with two of these inspections having to take place in dry dock twice every five years.

The in-water hull cleaning methods are in general differentiated by intensity, which in this study is divided into three levels low, medium, and high. Low intensity is a relatively gentle cleaning method for mostly soft fouling, high intensity corresponds to more aggressive cleaning to remove hard fouling such as calcareous organisms, and medium intensity is between the two. The frequency of the cleaning in the scenarios is largely divided into three categories: no cleaning, 1–3 times cleanings per year at scheduled timing, or cleaning is initiated whenever the hull surface roughness reaches certain trigger conditions. The trigger for cleaning is either when the upper confidence interval of the fouling rating reaches NSTM 40 (the minimum level of hard fouling) or when a user-defined propulsion penalty is reached. On the other hand, after the maintenance activities described above, such as initial coatings, touch-ups, or IWHC, are implemented, the hull surface roughness is assumed to return to a certain level (included in *Supplementary materials: Assumption used in HullMASTER*). If the hull surface roughness at the scheduled time for IWHC is in better condition than the initial hull roughness after the hull maintenance described in Table S2, the cleaning will be delayed until the hull surface is more fouled.

These IWHC scenarios are applicable only to copper-based antifouling coatings and inert coatings, excluding silicone-based foul-release coatings. According to the paint maker's guidelines, due to silicone-based coating's inherent self-cleaning properties and smooth surface resistance to fouling, they do not require hull cleaning except in special cases of prolonged stay in a highly fouling environment or very inactive ship operation (PPG, 2020). In practical terms, they are susceptible to abrasion and can be easily damaged if not carefully managed during the in-water cleaning process (Barnes, 2020).

2.3. Data analysis

The main objective of this study is to explore sustainable hull management strategies using the case of RoPax vessels operating in the Baltic Sea region. To this end, the study simulates the four RoPax vessels introduced in Section 2.2.2 sailing their routes for 10 years while implementing the 93 different hull maintenance scenarios presented in Section 2.2.3. Based on the simulation results, the economic, social, and environmental impacts and costs of each scenario can be analyzed in Section 3. Cost-benefit analysis is performed by comparing the relative cost difference between the baseline scenario and the scenario of interest. Here, the baseline scenario is selected as the most common coating option, copper coating, with no specific hull maintenance (dry-docking interval of 3.3 years and no IWHC), to identify the effects of hull management, while the scenario of interest corresponds to the optimal hull maintenance strategy that minimizes economic losses and socio-environmental damage. In addition, the analysis examines the fuel and emission reduction effects under the best-case scenario for each ship's coating type compared to the baseline scenario. Finally, this study aims to propose practical guidelines for sustainable hull management of vessels operating in the Baltic Sea region.

3. Results

3.1. Overview of cost-benefit analysis and best scenario

Fig. 4 summarizes the simulation results for the four RoPax vessels performed using HullMASTER for the 93 hull maintenance scenarios outlined in Fig. 3. The x- and y-axes in the figure represent the difference in operator's costs and socio-environmental costs due to biofouling and hull maintenance compared to the baseline scenario over the full 10 year-period. Here, the baseline scenario corresponds to the worst case of the hull maintenance scenarios for copper coatings analyzed on each RoPax vessel (copper coating, 3.3 years of dry-docking interval, no IWHC).

The study found that optimal hull management can lead to a difference of up to €9.3 million in operator costs and €7.9 million in socio-environmental damage costs for 10 years of ship operation compared to the baseline scenario. The largest savings, both in terms of operator and in socio-environmental damage costs, were observed for the foul-release coating scenarios. In addition, there can be a considerable cost variance depending on which hull maintenance scenario is applied to the same ship, as seen from the scattered samples in the figure. The trend of the cost differences varies by vessel, which is attributed to the fouling pressure and environmental characteristics of the vessel's sailing region, and the vessel-specific operational profiles. In particular, RoPax 1 and RoPax 2 show a large difference in operator costs for hull maintenance compared to socio-environmental damage costs due to the high fouling pressure in the Skagerrak/Kattegat region. In contrast, RoPax 3 and RoPax 4, which operate in the Baltic Proper region, show relatively larger differences in socio-environmental costs due to the damage cost of marine eutrophication caused by nitrogen (N) deposition from NOx emissions. The operational profile of the vessel also affects the fuel savings and the resulting savings on emissions. For instance, the RoPax 3 operates at a lower average speed than other vessels, which results in a reduced absolute size of cost savings from hull management. Conversely, the RoPax 4, which operates at higher speeds, has the opposite effect.

Table 2 provides a detail of the best maintenance scenarios for each vessel and coating type. Here, the best-case scenario is the one that maximizes savings for both operators and society compared to the baseline scenario. Since the best scenario for both operator and the society coincide for all three coating types, the scenario with the largest combined total savings is selected.

For inert and copper coatings, the best-case scenario is to maintain a drydocking interval of 3.3 years, performing two to three and one to two gentle IWHC per year, respectively. In particular, inert coatings, which lack antifouling properties, necessitate more frequent cleaning due to relatively faster fouling growth on the hull surface compared to copper coatings. Furthermore, differences in cleaning frequency are observed between vessels operating in the Skagerrak/Kattegat and the Baltic Proper region. These results demonstrate that delaying dry-docking by regularly performing gentle IWHC that minimizes paint wear is an effective way to reduce potential environmental impacts while achieving economic benefits.

On the other hand, all scenarios of foul-release coatings ($n = 3$) assuming no IWHC perform well compared to the baseline scenario of copper coatings. Among the foul-release coating scenarios, reducing the dry-docking interval to two years is the most effective strategy to save total costs. However, the savings in these costs between scenarios are not that large when considering 10 years of cost accumulation. In addition, the difference in operator's costs is likely to be smaller in practice as the current calculation only includes the costs associated with the hull surface treatment in drydock, excluding dock fees and losses due to downtime.

In addition, a double peak shape is noticeably observed (Fig. 4a and b) in the density plots for the operator's cost and socio-environmental cost of copper coatings. This can be attributed to the difference in the

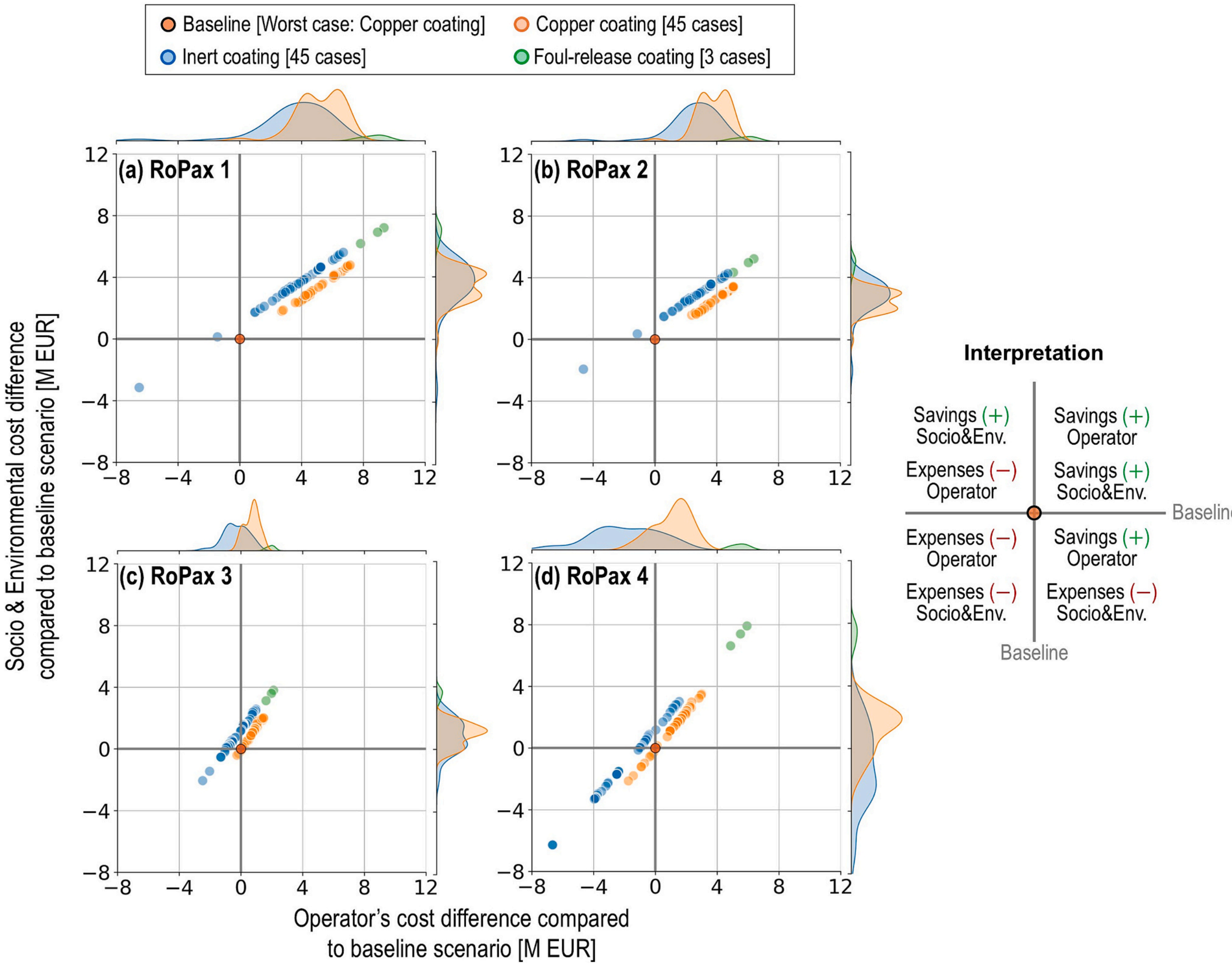


Fig. 4. Operational and socio-environmental cost differences due to biofouling and hull maintenance of 93 hull maintenance scenarios for four RoPax vessels in comparison to the baseline scenario (worst case of the copper coating). A positive value implies cost savings compared to the baseline scenario, whereas a negative value indicates losses compared to the baseline. All amounts are in millions of euros (M EUR) and are cumulative costs for a 10-year ship operation period.

application of "gentle cleaning" and "aggressive cleaning" in the in-water hull cleaning scenario. Similar to copper coatings, inert coatings also show cost differences based on cleaning intensity, but this trend is not evident in the figure as the cost differences for the hull maintenance scenarios are widely spread.

3.2. Bunker penalty and emissions

The cumulative bunker savings of a 10-year ship operation under the best-case scenario compared to the baseline scenario for each coating type listed in Table 2 are depicted in Fig. 5. The figure displays two sets of error bars: the solid error bars represent the 95 % confidence intervals of the bunker savings estimates assuming the average range of hull roughness conditions in Table S2, while the dashed error bars indicate the confidence intervals when applying the lower and upper bounds of hull roughness conditions. As illustrated, when the variation in hull roughness is included in the analysis (the highest and lowest reported values in Table S2), the overall uncertainty increases considerably (refer to the dashed error bars in Fig. 5). The hull roughness after dry dock maintenance and underwater hull cleaning may vary from ship to ship and case to case. Additionally, hull roughness data listed in Table S2 is based on a limited number of ships and exhibits large variations, which may affect the reliability of the estimates. Since the primary aim of this study is to assess how different antifouling strategies influence fouling growth, subsequent analyses will focus on scenarios that exclude roughness variation (as represented by the solid error bars).

The statistical significance of this analysis was identified by comparing the mean and confidence interval, considering that a statistically significant difference can be inferred when the 95 % confidence interval of the best-case scenario for each coating does not overlap with zero (the baseline scenario). The solid error bars indicate that the best scenario for all coating types shows a statistically significant difference within the 95 % confidence interval compared to the baseline scenario. The results also suggest that proper hull maintenance can significantly reduce fuel consumption for all coating types compared to the baseline scenario.

For all RoPax vessels analyzed, foul-release coatings demonstrate the most efficient bunker savings on average. Specifically, for RoPax 4, the best-case scenario for foul-release coatings shows a statistically significant amount of bunker savings compared to inert coatings, based on the average hull roughness. Copper coatings perform slightly better than hard coatings but are not as effective as foul-release coatings. Additionally, best-case scenarios for both copper and inert coatings require IWHC at ports, which may bring up practical and legal challenges. For example, in the port of Malmö (Sweden) IWHC is only allowed on biocide-free coatings (Granhag et al., 2023) and in the US, IWHC is banned outright or is actively discouraged in many locations based on concerns about introduction of non-native species and input of toxic chemicals (McClay et al., 2015). Guidelines for IWHC are in review 2024 and connected to the IMO Biofouling Guidelines (2023).

Table 2
The best practices by ship and coating type among hull maintenance scenarios (DD interval and IWHC intensity and frequency) analyzed in this study.

Vessel No. (Sailing region)	Coating type	DD interval	IWHC intensity	IWHC frequency
RoPax 1 (Skagerrak/ Kattegat)	Inert coating	3.3 years	Scheduled (low intensity)	IWHC 2–3 times/year (total 27 times)
	Copper coating	3.3 years	Scheduled (low intensity)	IWHC 2 times/year (total 20 times)
	Foul-release coating	2 years	No cleaning	No cleaning
RoPax 2 (Kattegat/ Danish Straits)	Inert coating	3.3 years	Scheduled (low intensity)	IWHC 2–3 times/year (total 27 times)
	Copper coating	3.3 years	Scheduled (low intensity)	IWHC 1–2 times/year (total 19 times)
	Foul-release coating	2 years	No cleaning	No cleaning
RoPax 3 (Baltic Proper)	Inert coating	3.3 years	Scheduled (low intensity)	IWHC 2–3 times/year (total 24 times)
	Copper coating	3.3 years	Scheduled (low intensity)	IWHC 1–2 times/year (total 15 times)
	Foul-release coating	2 years	No cleaning	No cleaning
RoPax 4 (Baltic Proper)	Inert coating	3.3 years	Scheduled (low intensity)	IWHC 2–3 times/year (total 22 times)
	Copper coating	3.3 years	Scheduled (low intensity)	IWHC 1–2 times/year (total 12 times)
	Foul-release coating	2 years	No cleaning	No cleaning

There is a difference in fuel savings depending on the vessel's operational area and profile. Notably, RoPax 1 and RoPax 2, which operate in the Skagerrak/Kattegat region where fouling pressure is high, can achieve greater fuel savings through hull maintenance compared to RoPax 3 and RoPax 4, which operate in the Baltic Proper. Moreover, since RoPax 3 is relatively less active than other vessels, the potential savings from hull management are expected to be large. However, due to its low operating speed, the absolute fuel savings from hull management are relatively smaller compared to the other three investigated ships.

The increase in energy consumption due to hull fouling results in the emission of various pollutants into the atmosphere and ocean. The emissions considered in this study include greenhouse gases (CO_2, CO, CH_4, N_2O, BC) that contribute to climate change, substances harmful to human health (NOx, SOx, PM2.5, NMVOCs), N deposition (originating from NOx) that contributes to marine eutrophication, and biocide and metal release (Cu and Zn) from antifouling coatings that affect marine ecosystems (Jalkanen et al., 2021; Ytreberg et al., 2021).

Fig. 6 illustrates the relative amount of pollutants emitted over a 10-year period in the best-case scenario by coating type, categorized by impact category, compared to the baseline scenario. The emissions to the atmosphere shown in Fig. 6a–d essentially follow the same trends as the bunker savings by vessel and coating type in Fig. 5, as they are estimated using emission factors associated with energy penalties. The

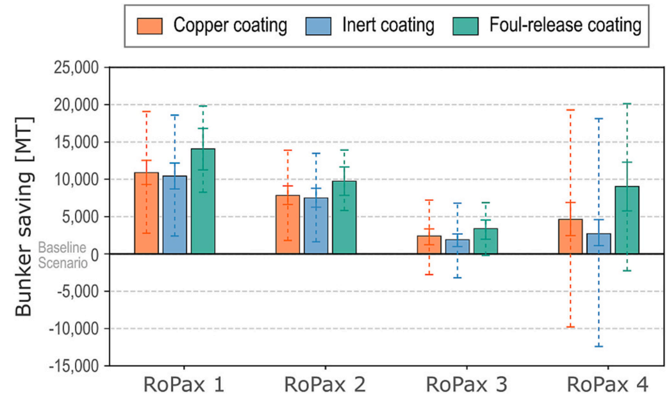


Fig. 5. Cumulative fuel savings for a 10-year ship operation period in the best-case scenario compared to the baseline scenario by coating type. A positive value implies fuel savings compared to the baseline scenario, whereas a negative value indicates losses compared to the baseline. The solid error bars represent the 95 % confidence intervals of the bunker savings estimates when assuming the average range of hull roughness conditions in Table S2 (*Supplementary materials: Assumption used in HullMASTER*), while the dashed error bars in the bar plots represent the confidence intervals when applying the lower to upper bounds of the hull roughness conditions.

analysis shows that the best-case scenarios for all coatings significantly reduce pollutant emissions compared to the baseline scenario, particularly for emissions such as CO_2, NOx, N_2O, and N.

On the other hand, the amount of Cu and Zn released by the biocidal antifouling coatings is influenced by the duration the coated surface is immersed in water, the specific conditions of the seawater environment, and the application of IWHC. As shown in Fig. 6e, the non-biocide coating options can reduce the inputs of Cu and Zn by approximately 470–490 kg and 112 kg, respectively, depending on the vessel, compared to the worst-case scenario of copper coating. For the best-case scenario of copper coatings, additional inputs of Cu and Zn may occur due to the implementation of IWHC events, and the extent of such inputs can vary depending on the intensity of the cleaning. The best-case scenario for copper coating in this study assumes a low-intensity cleaning technique that minimizes abrasion; under this scenario, the additional inputs of Cu and Zn due to IWHC are estimated to be 0.3–0.7 kg and 0.9 kg, respectively, compared to the baseline scenario. However, for a similar frequency of IWHC with medium-intensity cleaning, the additional inputs of Cu and Zn reach 25–55 kg and 31 kg, respectively. Furthermore, in scenarios with high-intensity IWHC, the release amounts of Cu and Zn can increase to approximately 100–126 kg and 48–49 kg.

3.3. Cost comparison between baseline and the best scenarios

The differences in operator costs and socio-environmental costs, along with their breakdowns, in the best-case scenario by coating type compared to the baseline scenario are illustrated in Fig. 7. Regarding operator costs, the average cost savings over 10 years of ship operation scenarios are between €2.1 million and €9.3 million for foul-release coatings, between €1.4 million and €7.1 million for copper coatings, and between €0.9 million and €6.7 million for inert coatings. Notably, all scenarios show significant cost differences compared to the worst-case scenario of copper coating, except for the best-case scenario of inert coating for RoPax 3 and 4. The primary driver of operator cost savings is the reduction in fuel consumption, which substantially exceeds hull maintenance costs. In comparison to the baseline scenario, the best-case scenario for foul-release coatings incurs losses due to high paint application costs, while that for copper and inert coatings is heavily influenced by IWHC costs.

In terms of socio-environmental costs, foul-release coatings yield the

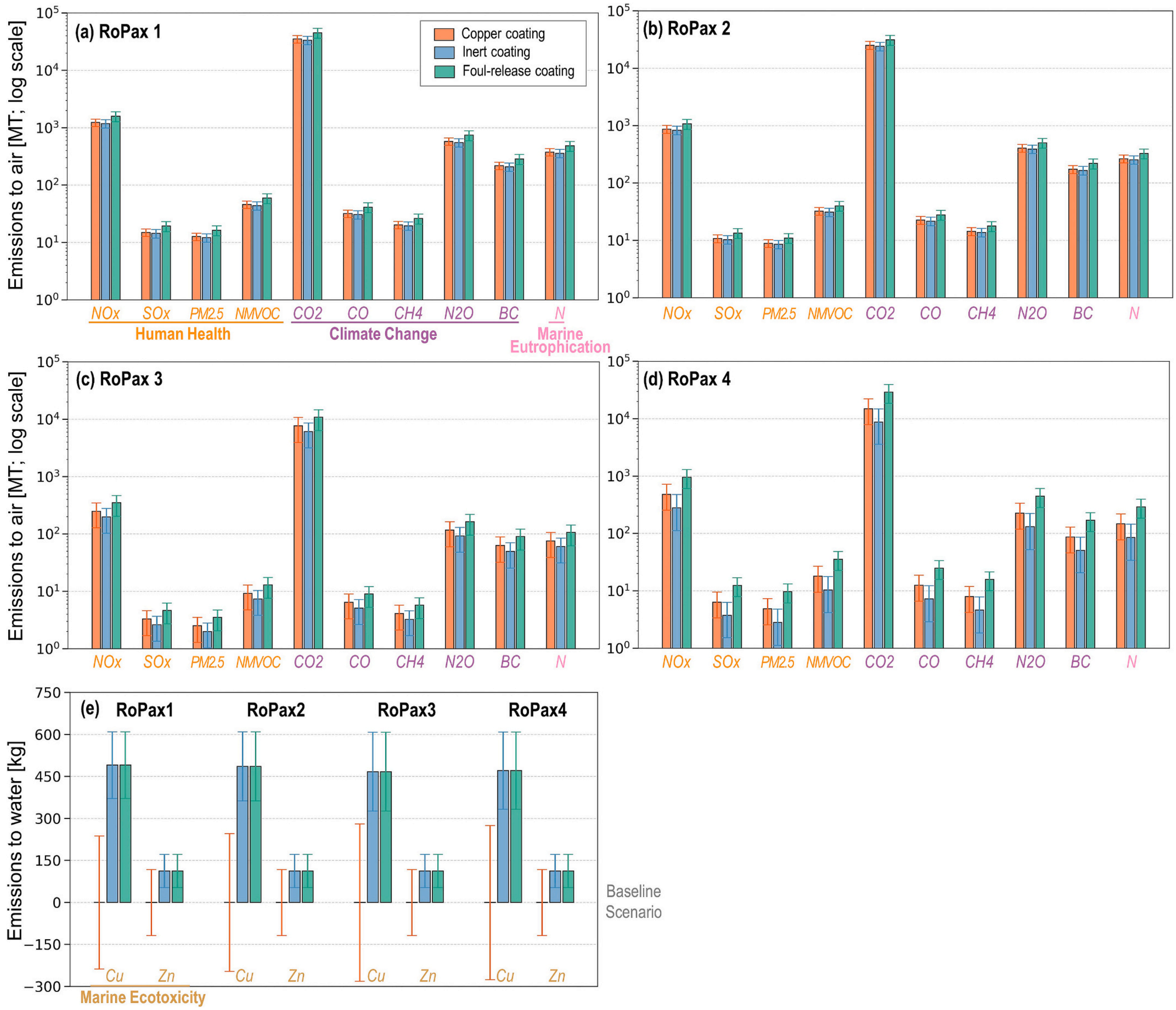
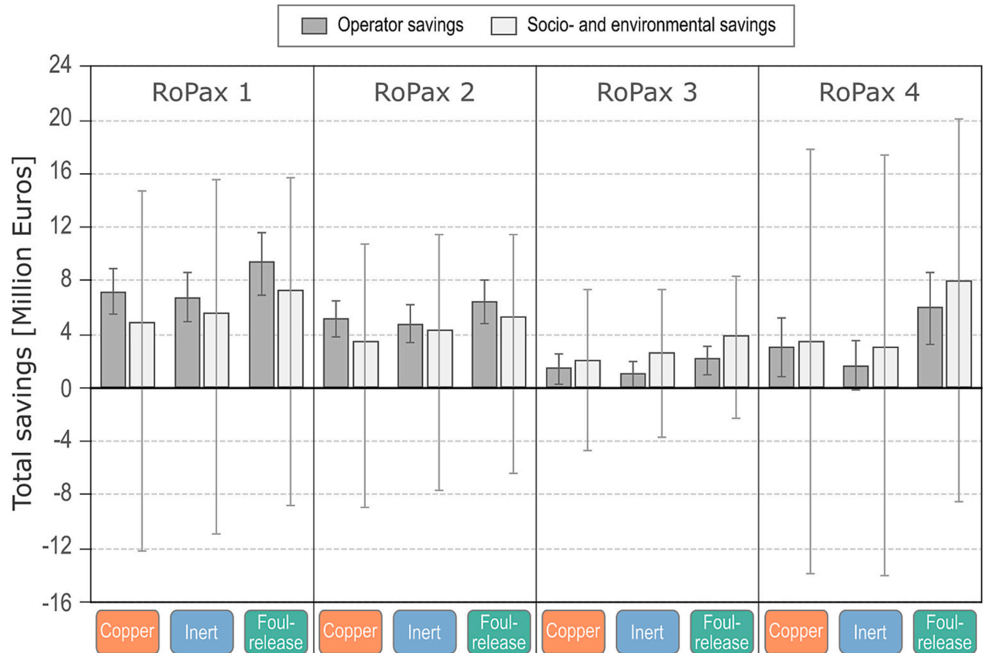


Fig. 6. Cumulative emissions savings for a 10-year ship operation period in the best-case scenario compared to the baseline scenario by coating type. Figs. (a)-(d) correspond to the different emissions released into the atmosphere that contribute to human health, climate change, and marine eutrophication, with the y-axis on a logarithmic scale. Among these, emissions related to climate change are converted to amounts equivalent to metric tons of carbon dioxide (mt CO_2eq). Fig. (e) shows the savings for releases of Cu and Zn into water associated with marine ecotoxicity. The amount of all emissions is calculated based on the average range of the hull roughness condition.

greatest average cost savings (€3.8 to €7.9 million), followed by inert coatings (€2.6 to €5.6 million) and copper coatings (€2.0 to €4.8 million). However, the 95 % confidence intervals for socio-environmental costs do not show a significant difference between these best-case scenarios and the baseline scenario. Overall, the socio-environmental damage costs involve large uncertainty since the uncertainty caused by the wide range of estimates of the damage costs for each item has propagated into the uncertainty of emissions. For example, this trend is particularly pronounced in the costs of climate change damage, where a 95 % confidence interval for the average social value of carbon ranges from approximately €22/ton to €210/ton CO_2 (Nordhaus, 2017).

For RoPax 1 and RoPax 2, operating in the Skagerrak and Kattegat regions, proper hull maintenance for each coating type results in the greatest savings in socio-environmental costs, especially in damage costs related to human health and climate change. Conversely, RoPax 3 and RoPax 4, which operate in the Baltic Proper region, can substantially reduce marine eutrophication damage caused by N deposition, with the resulting cost savings accounting for the largest portion of the socio-environmental cost. The amount of N deposition contributing to marine eutrophication is calculated by considering the percentage of N contained in NOx, as depicted in Fig. 6. However, the expected damage is calculated based on the extent to which the maximum allowable input (MAI) for N and phosphorus in the region is exceeded, as defined by HELCOM and the Baltic Sea Action Plan (BSAP) for the entire Baltic Sea and its sub-basins (Svendsen et al., 2015). In Kattegat, since no additional N reduction is required to achieve good environmental status, damage caused by NOx emissions (and N deposition) is not considered. In the Baltic Proper region, the cost savings of marine ecotoxicity damage due to the use of non-biocide coatings are noticeable.



	RoPax 1 Copper	RoPax 1 Inert	RoPax 1 Foul-release	RoPax 2 Copper	RoPax 2 Inert	RoPax 2 Foul-release	RoPax 3 Copper	RoPax 3 Inert	RoPax 3 Foul-release	RoPax 4 Copper	RoPax 4 Inert	RoPax 4 Foul-release
Operator savings (M€)	7.2	6.7	9.3	5.1	4.7	6.4	1.5	1.0	2.1	3.0	1.6	5.9
Fuel	103%	105%	102%	104%	107%	103%	110%	131%	108%	104%	118%	103%
Dry dock maintenance	0%	-1%	-2%	0%	-1%	-3%	0%	-6%	-8%	0%	-4%	-3%
IWHC	-3%	-4%	0%	-4%	-6%	0%	-10%	-25%	0%	-4%	-14%	0%
Socio/Env. savings (M€)	4.8	5.6	7.2	3.4	4.3	5.2	2.0	2.6	3.8	3.5	3.0	7.9
Human health	74%	60%	63%	74%	56%	59%	36%	22%	26%	40%	27%	35%
Climate change	26%	21%	22%	26%	20%	21%	14%	8%	10%	15%	10%	13%
Marine ecotoxicity	-0.02%	18%	14%	-0.03%	24%	19%	-0.09%	38%	26%	-0.04%	33%	12%
Marine eutrophication	-	-	-	-	-	-	51%	32%	38%	45%	30%	40%
Total savings (M€)	11.9	12.3	16.6	8.5	9.0	11.6	3.5	3.6	5.9	6.5	4.6	13.9

Fig. 7. Operator, socio-environmental and total cost savings, and detailed cost breakdown for the best-case scenario compared to the baseline scenario over 10 years of ship operation. The numbers in bold are the specific category that has the strongest impact (in %) on the total saving for operator and soc./env cost respectively. The cost values shown in the table are rounded to one decimal place.

4. Discussion

4.1. Sustainable hull maintenance strategies

4.1.1. Coating type

The cost-benefit analysis of the RoPax vessels shows that the choice of coating type significantly influences the operator's costs, as well as societal and environmental damage costs due to biofouling and hull maintenance. Among the evaluated coating types, the biocide-free foul-release coating was found to be the most sustainable option on average in the Baltic Sea and its neighboring waters (refer to Fig. 7). This is due to the fact that, even with the high cost of paint application, the overall superior antifouling effectiveness minimizes social and environmental damage such as human health, climate change, and marine eutrophication, as well as preventing the release of biocides into the marine environment. Eventhough the performance of the foul-release coating was derived from static immersion testing and non-cleaning conditions, it is likely that the antifouling effectiveness would be enhanced under actual ship operating conditions.

Nevertheless, since the study does not account for hull surface damage from external shocks or contacts, there might be practical difficulties in ship operations. Due to their vulnerability to mechanical damage, silicone-based foul-release coatings may not be suitable for cases that require frequent berthing and ship-to-ship operations or in areas that are covered with ice in winter, including some areas adjacent to the Baltic Sea (Oliveira et al., 2022). In such cases, abrasion-resistant coatings can be considered as a practical alternative (Watermann et al., 2021). However, as can be seen in Fig. 4, the variation in cost for different hull maintenance scenarios for inert coatings is very large compared to other coating options. This suggests that ship operators need to implement the right hull management strategy for their vessels to realize significant cost savings. It could also be advantageous to consider applying different coatings near the waterline and niche area, where there is much possibility for mechanical damage.

4.1.2. Hull surface treatment in dry dock

The case study of RoPax vessels indicates that, despite the potential cost savings from reducing the dry-docking intervals, its impact is relatively minor compared to other hull maintenance factors. Notably, when comparing the worst and best-case scenarios for foul-release coatings, the difference between reducing the docking interval from 3.3 years to 2 years is trivial, despite the cumulative cost over 10 years. This stems from the limitation of the current cost-benefit analysis, which only considers maintenance costs associated with hull coatings in dry dock. Other dry-docking costs, such as inspection costs, dock rental fees, and revenue loss due to vessel off-hire, are not accounted for. Consequently, in practice, shorter dry-docking intervals may increase the cost of lost revenue due to these additional factors. In addition, as passenger ships are required by SOLAS regulation I/7 (IMO, 2020) to undergo an annual inspection of the bottom hull and two dry-dock inspections in any five-year period, a number of variables are expected to affect the dry-docking timing, including not only the fouling condition of the hull, but also the operating schedule, maintenance and repair schedule of machinery, and renewal of certificates. As seen in the best scenarios of inert coatings and copper coatings, the cost of hull treatment in dry dock, including spot blasting and paint touch-up, is more burdensome than on-site hull cleaning, making the strategy of delaying dry-docking while maintaining regular IWHC more cost-effective.

4.1.3. In-water hull cleaning

Silicone-based foul-release coatings are not recommended for hull cleaning according to the paint manufacturer's instructions except in the special case of prolonged stays in environments of high fouling pressure or very inactive vessel operations. Rather, they are vulnerable to abrasion and can be easily damaged if not carefully managed during the underwater cleaning process. For copper and inert coatings, in addition to selecting the coating type, the right interval and intensity of IWHC are identified as critical factors in cost savings. Specifically, gentle IWHC of 1–2 times and 2–3 times per year, respectively, is found to be the optimal scenario, resulting in significant cost savings compared to scenarios that did not include cleaning (operator's cost: €1.5–7.2 million (Copper coating), €1.0–6.7 million (Inert coating); socio & environmental cost: €2.0–4.8 million (Copper coating), €2.6–5.6 million (Inert coating)). Furthermore, IWHC should be implemented taking into account the biofouling pressure level in the region where the ship operates. In particular, the RoPax vessel cases demonstrate that areas with high biofouling pressure, such as Skagerrak/Kattegat, require relatively more frequent cleanings compared to the Baltic Proper.

It can be observed that the intensity of hull cleaning is another factor contributing to the difference between operating costs and socio-environmental expenses. Timely hull cleaning with appropriate intensity can contribute significantly to reducing fuel consumption, as well as reducing the costs of damages related to human health, climate change, and marine eutrophication. However, it is important to recognize the potential damage to marine ecosystems due to toxic substances released from biocide coatings and invasive species introduced from biofouling. This study has shown that, despite applying the same copper coating, the cumulative amount of Cu introduced over ten years on the same vessel can vary from less than 1 kg to over 100 kg, depending on the established IWHC intensity scenarios. Given that there are 217 RoPax vessels and 9240 IMO-registered vessels operating in the Baltic Sea (HELCOM, 2023b), the potential impact of such IWHCs on marine ecosystems could be substantial. Thus, managing the toxic substances generated during and after IWHCs is a critical issue.

Due to local environmental issues and the presence of invasive species, more and more ports are implementing bans or limitations on traditional hull cleaning techniques. Although some ports permit IWHC, specific regulations are in place to ensure the proper collection and disposal of all debris (Krutwa et al., 2019; Watermann et al., 2021). Moreover, some ports only permit hull cleaning operations during daylight hours to ensure the safety of divers, and limited resources at the port can pose challenges to carrying out unscheduled hull cleaning operations (Doran, 2020). As a result, it is necessary for ship operators to proactively schedule hull cleaning, considering factors such as routes, schedules, and local regulations. They should also aim to minimize socio-environmental impacts by implementing sustainable hull management and vessel operations, including in-water cleaning and debris collection systems.

4.1.4. Societal benefits

According to the best hull maintenance scenario for each ship and coating type derived in this study, economic losses and socio-environmental damage costs are minimized when the mean fouling level of the hull is kept at or below the level of light slime. In other words, the presence of biofilms that gradually develop on the hull during ship operation should not be overlooked, as it can significantly impact long-term operating costs.

In this study, the cumulative costs associated with 10 years of ship operation were analyzed to evaluate the costs of various hull management strategies, which can be considered as a mid-to-long-term assessment given that the typical lifespan of a ship is around 20–25 years (Chatzinikolaou and Ventikos, 2014). The economic benefits associated with different hull management strategies may not be apparent initially, especially during shorter operating periods (e.g., within 5 years), but tend to become increasingly evident over time. Additionally, while this study does not include a specific assessment of the vessel's residual value, it is clear that appropriate hull management can extend the operational lifespan of the ship and increase its residual value. The costs of socio-environmental damage and recovery are mostly borne by society, and ship operators may not be directly involved in these aspects. Therefore, ship operators need to be aware of this and establish a long-term, sustainable hull management strategy based on a ship-tailored assessment that takes into account the ship characteristics, operation profile, and sailing region.

4.2. Limitations and future research

Several assumptions and limitations related to HullMASTER and the scenarios applied have been identified, which can potentially introduce uncertainty in the analysis results. This study specifically targets four RoPax vessels operating in the Baltic Sea and adjacent areas, and it should be noted that the findings may not apply universally to all ships and regions. Due to differences in design characteristics, environmental conditions at ports, and operational patterns among different ship types, the impacts on biofouling growth rates, energy consumption, and underwater emissions may vary. Therefore, to identify ship-tailored solutions, individual evaluations based on the unique characteristics and operating conditions of each vessel are necessary through repeated simulations of viable hull management scenarios.

The biofouling growth trend modeled in HullMASTER is based on static immersion tests of coated panels conducted at various sites over approximately one year, with seawater salinity being a primary parameter. However, it is important to note that the analysis tool used in the study was based on static immersion tests and did not account for the detachment effect of organisms during motion. This consideration is particularly crucial for foul-release coatings, which not only prevent fouling due to their surface amphiphilic properties but also cause marine organisms attached to the hull to fall off when the ship moves at or above a certain speed (Davidson et al., 2020). Additionally, other factors such as seawater temperature, pH, and light conditions at the berth can also influence biofouling growth.

Our study did not consider the risk and associated costs of introducing non-native species that might be caused by hull management. However, the operation of vessels such as RoPax 1, which transits the Baltic Sea and neighboring areas from outside waters, can pose risks of introducing and spreading these species. Nevertheless, effective hull management on ships could reduce this risk of foreign species introduction. Furthermore, it is assumed that no separate effluent treatment is conducted after IWHC. If paint particles generated during the hull cleaning process are collected through a capture system, it could reduce the toxic damage to the marine ecosystem caused by biocidal coatings.

In this research, we performed a cost-benefit analysis using the 95 % confidence interval of LSMGO prices from 2020 to 2023, but the minimum and maximum fuel costs during this period differed nearly five-fold. Considering that bunker penalties associated with hull fouling make up the largest portion of the operational costs, such volatility in fuel prices introduces considerable uncertainty into our life cycle cost analysis results. Furthermore, scenarios involving other fuel options, such as IFO380 (with an open loop scrubber), that are almost twice as cheap as LSMGO will have higher marine ecotoxicity damage costs (due to input of scrubber discharge water), but lower operator costs due to fuel penalties (Lunde Hermansson et al., 2024). In such cases, the choice of hull management solution implemented on a vessel may also be affected. Additional information on the variability of fuel prices can be found in *Supplementary materials: Price volatility by time of year and fuel type*.

In conclusion, the various factors mentioned above could potentially lead to discrepancies in reality. In addition, estimates based on limited data, such as fouling growth rates, hull roughness, and damage costs, contain inherent uncertainties that propagate from one step to the next, increasing the uncertainty of the cost-benefit analysis results. Specifically, according to the data presented in Table S2, the initial hull roughness due to the hull maintenance event had a large deviation between the lower, average, and upper bounds. These uncertainties will need to be refined with more data collection and related research in the future.

Future research directions will include investigating the impact of vessel design characteristics on energy penalties and the resulting changes in hull maintenance solutions. Moreover, we plan to carry out follow-up studies to broaden the application of our tools. This will involve considering varying environmental conditions through field tests conducted across wider geographical areas and utilizing a more diverse set of input data.

5. Conclusion

This study conducted a cost-benefit analysis on 93 different hull maintenance scenarios for four RoPax vessels operating in the Baltic Sea region. The findings clearly demonstrate that adopting appropriate hull management practices enhances the economic benefits for operators and significantly reduces social and environmental damage. Notably, among the evaluated coating types, biocide-free foul-release coatings were found to be the best sustainable option for ships operating in the Baltic Sea region. This is due to their ability to prevent the release of biocides into the ocean as well as reduce fuel consumption and emissions to the atmosphere. However, due to vulnerability of silicone-based coatings to mechanical damage, in cases that require frequent berthing and ship-to-ship operations or in areas that are covered with ice in winter, abrasion-resistant coatings should be considered as a practical alternative.

For RoPax vessels, it was observed that reducing dry-docking intervals had relatively limited cost savings compared to other viable factors, given the short inspection schedule. It has been suggested that for coatings where hull cleaning is desirable, a strategy of regular IWHC could be a cost-effective alternative for hull condition maintenance and delaying dry-docking. In addition, implementing IWHC at the optimal frequency (approximately 1–3 times/year depending on the vessel case) and with a gentle level of intensity played an important role in cost reduction. To minimize toxic substances that may be released during the hull cleaning process, ship operators should strive to minimize negative impacts on marine ecosystems through measures such as IWHC and debris collection systems. In conclusion, a ship-tailored hull management strategy that considers the vessel's unique characteristics, operating conditions, and sailing area should be established as a long-term goal for economically, socially, and environmentally sustainable ship operations.

The HullMASTER used in this study shows that it is capable of providing an upfront understanding of the economic and socio-environmental costs of a range of viable initiatives in terms of hull management compared to conventional practices and can assist in the decision-making process. However, as shown in the cost-benefit analysis, the uncertainties inherent in various factors such as fouling growth estimates, hull roughness, damage costs, and other factors will need to be further explored and refined through data collection and research in collaboration with more shipping stakeholders. These findings are expected to make an important contribution to the development and application of more environmentally sustainable and responsible hull management measures in the Baltic Sea region.

CRediT authorship contribution statement

Youngrong Kim: Writing – review & editing, Writing – original draft, Visualization, Software, Methodology, Investigation, Conceptualization. **Maria Lagerström:** Writing – review & editing, Visualization, Methodology, Investigation, Conceptualization. **Lena Granhag:** Writing – review & editing, Project administration, Investigation, Funding acquisition, Conceptualization. **Erik Ytreberg:** Writing – review & editing, Project administration, Investigation, Funding acquisition, Conceptualization.

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. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.marpolbul.2024.117453.

Data availability

Data will be made available on request.

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