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(article starts on next page)

Cost-Benefit Analysis of Ship's Hull Maintenance Scenarios in the Kattegat and Danish Strait Route

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Abstract

This study conducts a cost-benefit analysis of various hull maintenance scenarios using the support tool HullMASTER. The analyses provide examples of a ship operating in the Kattegat-Danish Strait. This study indicates that increased hull roughness due to biofouling and hull maintenance, compared to hydraulically smooth hulls, can escalate operational and socio-environmental costs by 6 and 7.2 times. Among the evaluated coatings, non-biocidal foul-release coatings are identified as the most sustainable option by reducing climate change and health damage, and biocide release into the ocean. It also highlights the importance of proper maintenance and the need for sustainable long-term planning.

1. Introduction

The accumulation of marine organisms on a ship's hull, known as ship biofouling, decreases the operational efficiency of vessels, increases fuel consumption, and consequently elevates costs for shipping companies, *Schultz (2007)*. Furthermore, it has severe implications for human health and marine ecosystems due to the increased exhaust emissions and the release of toxic substances from anti-fouling paints applied to hulls, *Ytreberg et al. (2021)*. As a result, the appropriate management of ship biofouling has emerged as a critical task in ship operations.

The determination of an optimal hull management strategy is a complex process influenced by several factors, including the ship's size, operational profile, and sailing area, *Kim et al. (2022)*. Moreover, shipowners must consider not only the increased operational costs resulting from hull management strategies but also their implications for climate change, human health, and the marine environment. To address these concerns, it is essential to apply life cycle cost analysis to assess the economic performance and social impact of various technologies, enabling shipowners to select the most sustainable hull maintenance strategy.

In response to this challenge, *Oliveira et al. (2022)* developed HullMASTER (Hull MAint-nance STrategies for Emission Reduction), a tool designed to assist shipowners, operators, and other stakeholders in evaluating the economic and environmental costs of various ship hull maintenance strategies. Expanding on this work, in this paper, we employ HullMASTER to simulate various hull management scenarios for a ship navigating the Kattegat and Danish Strait and conduct an economic, social, and environmental cost-benefit analysis accordingly. Through this, we aim to understand how variations in hull management strategies affect costs in these water areas and propose sustainable hull management strategies that minimize the operational costs for shipowners while contributing to social and environmental protection.

2. HullMASTER: Decision Support Tool for Hull Maintenance Strategies

HullMASTER is a tool designed to calculate and compare the operational, societal, and environmental costs of various hull maintenance strategies, such as the type of coating, docking frequency, in-water cleaning frequency, and hull treatment procedures applied to a specific ship. The operational costs include additional fuel costs due to biofouling, hull treatment during dry docking, and hull cleaning costs. Societal and environmental costs encompass the health and climate impacts of increased exhaust gases and the release of toxic substances due to biocidal coatings, as well as the costs associated with marine eutrophication and marine ecotoxicity. All costs resulting from hull roughness due to coating and biofouling are calculated in comparison to a hydraulically smooth hull. It is important to note that these costs modeled in HullMASTER do not reflect the absolute costs of ship operation. The tool was validated using approximately 40 years of cumulative operational data measured from nine ships operating in the Baltic Sea. The estimated propulsive penalties for the entire fleet indicated an average deviation of -3.2 ± 3.8%, which underscores the tool's substantial accuracy.

Fig.1 illustrates the overall composition of HullMASTER. The subsequent parts, 2.1 and 2.2, will delve into the main models that constitute this tool, specifically the hull fouling growth and biocide release. For a more detailed explanation of the principles and sources supporting HullMASTER, please refer to *Oliveira et al. (2022)*.

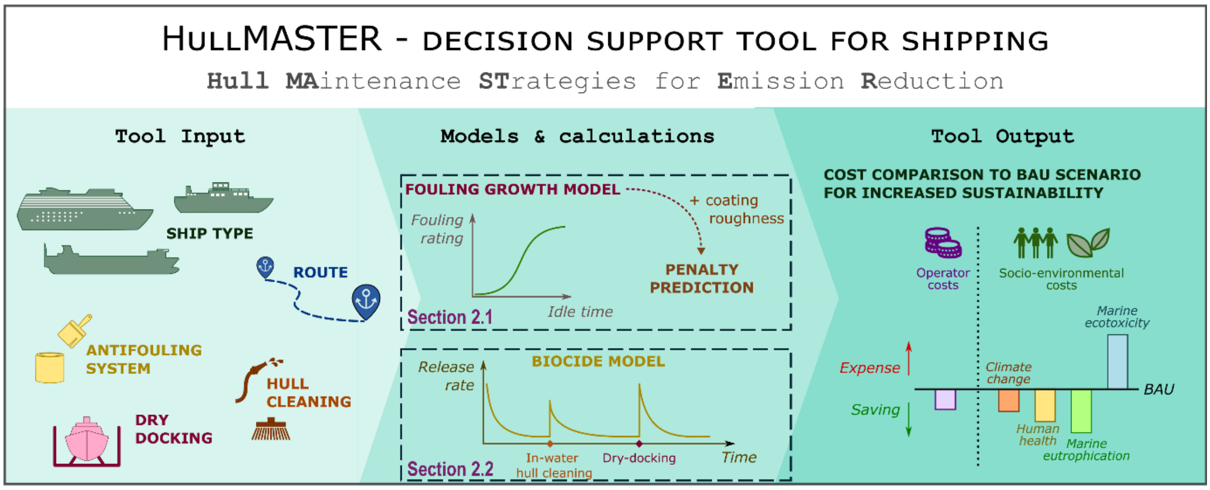


Fig.1: Configuration of HullMASTER

2.1. Hull fouling growth & Propulsive power penalty

The formation and growth rate of biofouling on a hull surface are influenced by several parameters. The most significant variables for predicting fouling growth rates in the Baltic Sea region are the accumulated idle time, *Oliveira and Granhag (2020)*, and salinity, *Wrange et al. (2020)*. The fouling growth model used in HullMASTER is based on data obtained from field experiments conducted in the Swedish coastal region, including the Baltic transition and the Baltic proper, *Lagerström et al. (2022)*. As shown in Fig.2, the degree of hull fouling is defined in reference to the frNSTM fouling rating, *US Navy (2006)*, and the cumulative fouling degree over time is fitted using a Gaussian curve, *Uzun et al. (2019)*. HullMASTER uses the seawater salinity and berthing time at the port of call as input parameters to calculate the cumulative fouling growth during the operation.

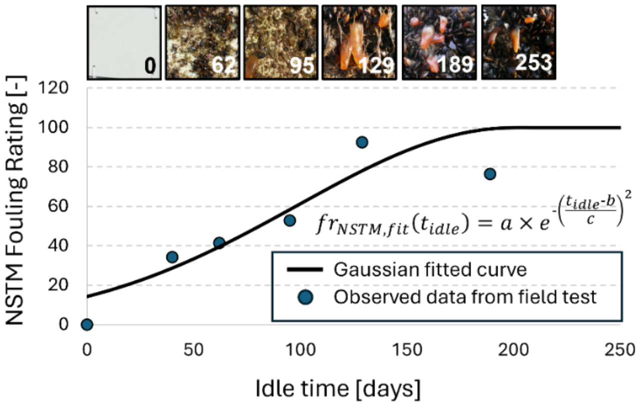


Fig.2: NSTM fouling rating over idle time based on the field test data

The condition of hull roughness is expressed as an equivalent sand grain roughness, and the roughness resulting from coating and biofouling is added to the hydraulically smooth surface. The increase in frictional resistance due to hull roughness is calculated using Granville's method, *Granville (1987)*, which utilizes the flat-plate similarity law scaling method. This allows the estimation of the ship's power penalties relative to the condition of a smooth hull.

2.2. Biocide release from anti-fouling coatings

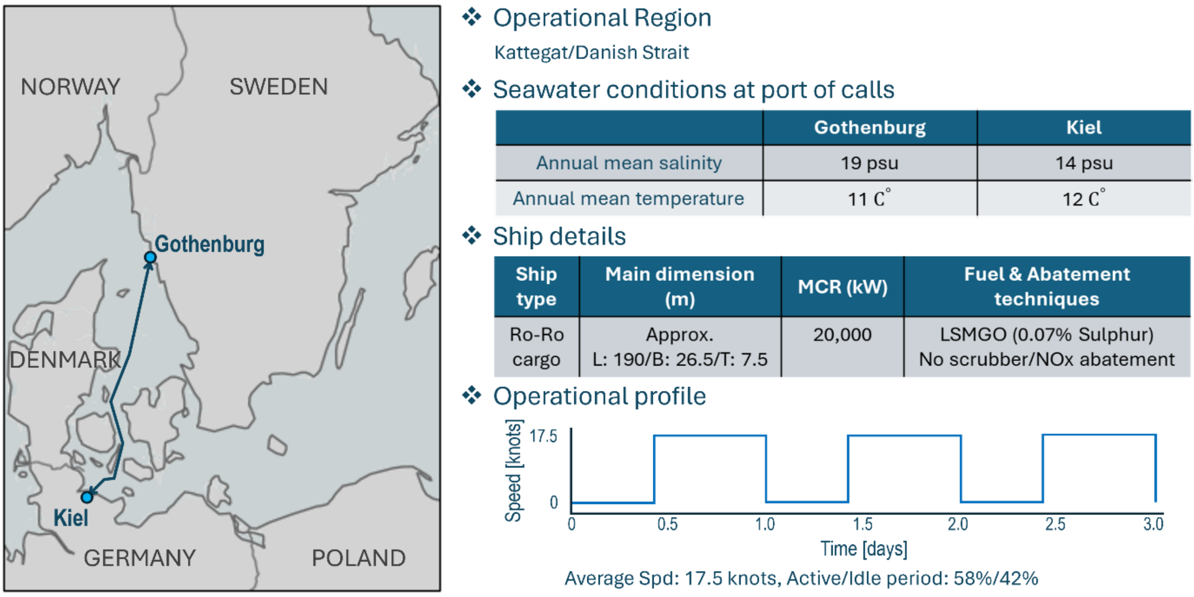
Most anti-fouling paints used on ships contain biocides like copper oxide to control marine fouling, which release biocides upon contact with seawater, *Ytreberg et al. (2022)*. Additionally, these coatings contain zinc oxide to prevent corrosion, *Lagerström et al. (2018)*. The release of these harmful substances is modeled in HullMASTER based on the average release rates in the Baltic Sea region.

The passive release rate of these hazardous substances into the water is determined based on data from *Lagerström et al. (2020)*, and a consistent decay ratio is applied to the release rate presented by *Valkirs et al. (2003)* to account for long-term emissions. Besides, additional anti-fouling compounds can be released during or after the hull cleaning event. This is estimated based on the weight content of biocides in the removed coating thickness, *Tribou and Swain (2017)*. The release of copper and zinc due to gentle cleaning methods causing negligible to moderate paint wear is referenced from *Soon et al. (2021)* and *Granhag et al. (2023)*. In contrast, aggressive cleaning methods that cause a higher level of wear are calculated using the paint removal values mentioned in *Morrisey et al. (2013)*. The increased passive release rate following cleaning events is modeled based on the study by *Earley et al. (2014)*.

3. Methodology

3.1. Selection of a ship case in the Kattegat-Danish Strait

This study performs a cost-benefit analysis of various hull maintenance scenarios for a ship sailing through the Kattegat and Danish Strait using HullMASTER. The case study utilizes a 190 m-class ro-ro ship that regularly operates the Kiel-Gothenburg route based on the ship's operational profile, Fig.3. The high-salinity seawater influx through the Baltic transition zone, such as Skagerrak and Kattegat, creates a gradient of decreasing surface salinity across the entire Baltic Sea. The Kattegat-Danish Strait route used in the case study is characterized by relatively high fouling pressure throughout the operating area. Meanwhile, the annual average temperature in the target area is around 11°-12°, but in some Baltic transition areas, it can rise to 30° in the summer and fall below freezing in the winter.



❖ Operational Region

Kattegat/Danish Strait

❖ Seawater conditions at port of calls

	Gothenburg	Kiel
Annual mean salinity	19 psu	14 psu
Annual mean temperature	11 C°	12 C°

❖ Ship details

Ship type	Main dimension (m)	MCR (kW)	Fuel & Abatement techniques
Ro-Ro cargo	Approx. L: 190/B: 26.5/T: 7.5	20,000	LSMGO (0.07% Sulphur) No scrubber/NOx abatement

❖ Operational profile

Average Spd: 17.5 knots, Active/Idle period: 58%/42%

Fig.3: Overview of ship operations in the Kattegat/Danish Strait used in case study

3.2. Hull maintenance scenarios

This study assumes that the ship selected in Section 3.1 operates the corresponding route for 10 years and employs HullMASTER to examine the variations in costs that arise from different hull maintenance scenarios. As shown in Table I, a total of 93 hull maintenance scenarios were considered, encompassing several factors such as coating type, dry docking period, and in-water hull cleaning method and frequency.

The scenarios cover three distinct categories of coatings that are frequently used on commercial ships: copper-based anti-fouling coatings, non-biocide foul-release coatings, and inert abrasion-resistant coatings. In all scenarios, it is assumed that the initial state of the hull is completely sandblasted and a new coating is applied. Then, during the 10-year ship operation period, it is assumed that the ship's hull surface will undergo spot-blasting and touch-up coating at the dry dock, as per the provided scenario.

The frequency of in-water hull cleaning is classified into three situations: no cleaning applied, 1-3 cleanings occurring per year, and cleaning triggered whenever the hull condition reaches certain conditions. The criteria for the cleaning trigger are when the upper limit of the confidence interval of the fouling rating grade reaches the NSTM 40 (the minimum level of hard fouling) or when it reaches the user-defined propulsion power penalty. Cleaning methods are divided into two categories according to intensity: gentle cleaning for soft-moderate fouling and more aggressive cleaning mainly for removing calcareous fouling. It is accompanied by negligible paint wear, moderate wear, and high-level wear, depending on the cleaning methods. These in-water hull cleaning scenarios are limited to copper-based anti-fouling coatings and inert coatings, and silicone foul-release coatings are not included because of their distinctive self-cleaning properties and smooth surfaces that resist fouling.

Table I: Hull maintenance scenarios used in the study (total 93 scenarios)

Coating type	Hull surface treatment in dry dock (Initial/Subsequent)	Dry docking interval (years)	In-water hull cleaning (IWHC) frequency	Cleaning intensity	Total number of scenarios
Inert abrasion-resistant coating	Full blasting with new coating/Spot blasting with touch-up coating	2/2.5/3.3	No IWHC	-	45 scenarios for each coating
			IWHC 1~3 times/year	Gentle cleaning (negligible or moderate paint wear) /Aggressive cleaning (high paint wear)	
Biocidal antifouling coating (copper-based)			IWHC trigger option Trigger I: NSTM FR 40 Trigger II: Power penalty 20/30/40/50%	Gentle cleaning (moderate paint wear)	
Biocide-free foul-release coating (silicone-based)	Full blasting with new coating/Spot blasting with touch-up coating	2/2.5/3.3	No IWHC	-	3 scenarios, assuming no IWHC event

4. Discussion

4.1. Cost-benefit analysis of hull maintenance scenarios

Fig.4 illustrates the results of simulating a 10-year operating scenario of a ship with 93 different hull maintenance strategies using HullMASTER. The x- and y-axes in the figure represent increased operational and socio-environmental costs due to biofouling and hull maintenance compared to hydraulically smooth hull surfaces, respectively. The arrows marked on the histogram show the best and worst cases in terms of cost for each type of coating. These graphs show the overall trend through the cost distribution between scenarios, and it should be noted that the absolute costs can vary depending on various factors constituting the cost and their definitions.

As can be seen from the distribution of scatters in the figure, there is a substantial cost difference depending on the hull maintenance scenario for the same route and vessel. For instance, within the set of 93 scenarios, the operator's expenses and socio-environmental damage costs can differ by up to 6 and 7.2 times, respectively, depending on the specific coating employed and hull maintenance method applied. Out of the coating types examined, foul-release coatings typically show lower increments in both operational costs and socio-environmental costs. Although copper coatings have a significant environmental impact compared to other non-biocidal coatings, they can be considered a cost-effective choice due to their substantial ability to reduce ship biofouling. Conversely, inert coatings show the largest deviation in operator and socio-environmental costs among the three coatings, depending on the hull management scenario.

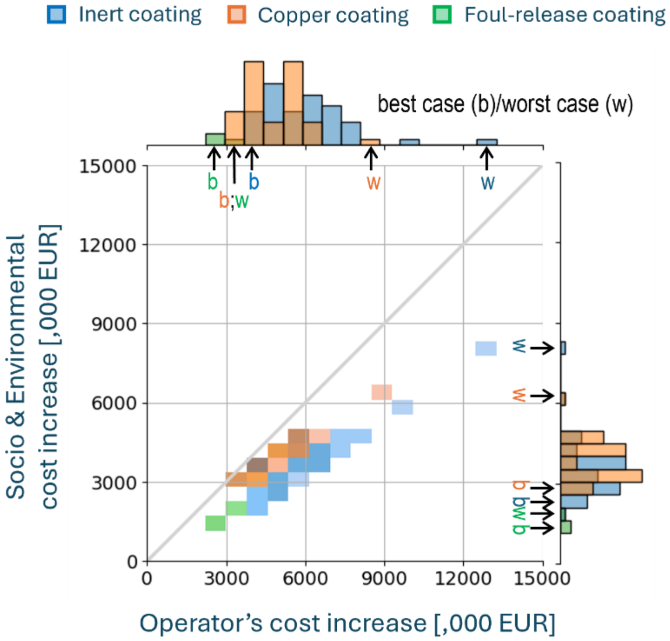
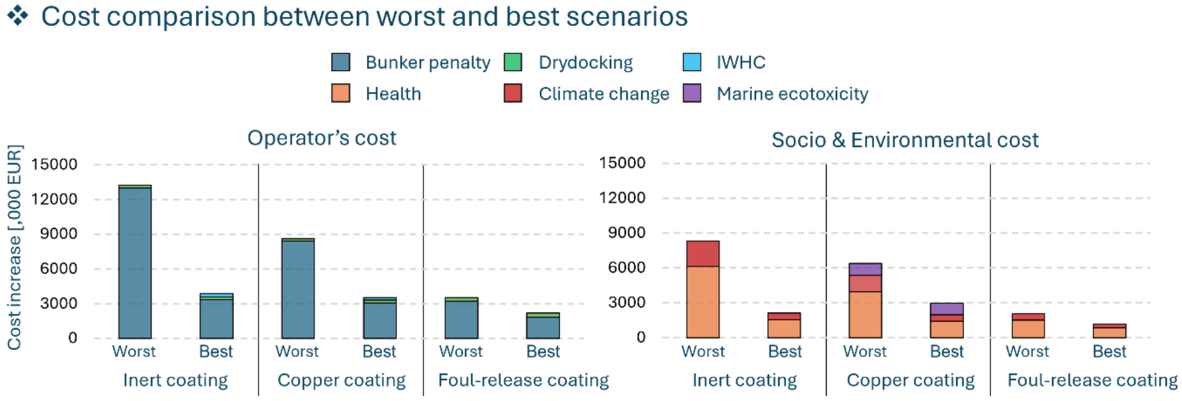


Fig.4: Distribution of increased operational and socio-environmental costs due to biofouling and hull maintenance in comparison to a hydraulically smooth hull surface of all scenarios

Fig.5 presents a comprehensive analysis of the highest (worst case) and lowest (best case) cost increments for each coating category, based on the 93 distinct scenarios depicted in Fig.4. The table below the picture displays the selected hull maintenance scenarios. Based on the findings of the cost-benefit analysis conducted in the Kattegat and Danish Strait, the additional expenses incurred from fuel penalties far exceed those from hull maintenance, including treatment and cleaning, in all types of coatings. The largest portion of socio-environmental cost increase is due to damage costs to human health, followed by climate change. However, when it comes to copper coatings, unlike other coatings that do not have biocidal properties, the expense of marine ecotoxicity damage caused by the release of biocides from the paint into the sea is taking a substantial part.

The most significant increase in operational and socio-environmental costs, when compared to a hydrodynamically smooth hull, arises from the neglect of underwater hull cleaning and infrequent dry dock maintenance. Looking at the most cost-effective scenarios analyzed, inert and copper coatings have the same dry dock interval of 3.3 years, during which in-water hull cleaning is performed 27 and 19 times during the simulated period, respectively. This demonstrates that keeping the hull roughness below a certain level leads to substantial reductions in fuel expenses for the operator, as well as damage cost reductions in terms of climate change and human health damage from a socio-environmental standpoint, when compared to the expense of hull maintenance. Nevertheless, when it comes to biocidal coatings, the release of higher amounts of anti-fouling substances during and after cleaning the hull can escalate the expenses associated with the damage caused to marine organisms. Therefore, it is preferable to conduct hull cleaning at suitable intervals, taking into account different socio-environmental consequences. Conversely, in the case of foul-release coatings, it is shown that reducing the dry dock interval is a more economically efficient option, assuming that in-water hull cleaning is not carried out.


❖ Cost comparison between worst and best scenarios

❖ Details of hull maintenance scenarios (worst ⟶ best)

	Inert coating	Copper coating	Foul-release coating
Hull maintenance scenarios	IWHC: 0 → 27 times in 10 years (gentle cleaning) DD interval: 3.3 yrs	IWHC: 0 → 19 times in 10 years (gentle cleaning) DD interval: 3.3 yrs	IWHC: No cleaning DD interval: 3.3 → 2.0 yrs

Fig.5: Comparison of cost increase between best and worst scenarios by coating type and corresponding hull maintenance scenarios

In our case study, despite its high paint application cost, the non-biocide foul-release coating emerged as the most sustainable option among the evaluated coating types. This is due to its effective anti-fouling properties, resulting in reduced emissions and minimized impact on human health while preventing the release of biocides, hence minimizing damage to the marine environment. Nevertheless, in regions that are covered by ice during the winter, including some regions adjacent to the Kattegat and Danish Strait, the silicone-based foul-release coating may not be appropriate because of its susceptibility to mechanical damage. In such cases, an abrasion-resistant coating may serve as an appropriate alternative. Copper coatings are widely utilized in both commercial ships and leisure boats globally, as they offer significant benefits in efficiently preventing the accumulation of organisms on the hull and are relatively easy to manage. However, they pose environmental risks due to the discharge of toxic substances and can potentially damage marine life and ecosystems. Hence, it is imperative to implement measures to curb the excessive utilization of biocides in anti-fouling coatings and to regulate the discharge concentration and rate of biocides to ensure sustainable operation. These efforts can enhance the responsibility of ship owners and make a substantial contribution to the protection of the marine environment.

4.2 Difference in operator's costs: Short vs Long-term hull maintenance strategies

Fig.6 presents a comparison of the cumulative operator's costs over time in the worst and best scenarios for the three different types of coatings. For inert coatings, the operational expenses in the best scenario, which includes cleaning, and the worst scenario, which excludes cleaning, are nearly identical for approximately one year following the initial coating application. This implies that the cost-effectiveness of hull cleaning in terms of fuel consumption reduction is not considerable during this period. However, beyond this timeframe, the cost savings achieved through hull cleaning become increasingly apparent in comparison to the expenses associated with hull management. In the case of copper-based anti-fouling coatings, the cost trends remain the same in both the worst and best scenarios for up to 2 years after the initial coating application. This is due to the fact that the NSTM fouling grade of the hull remains consistently below 20 throughout this time period, thus no in-water cleaning procedure is carried out. For silicone-based foul-release coatings, the cost difference becomes apparent as hull treatments progress and more dry dock events accumulate.

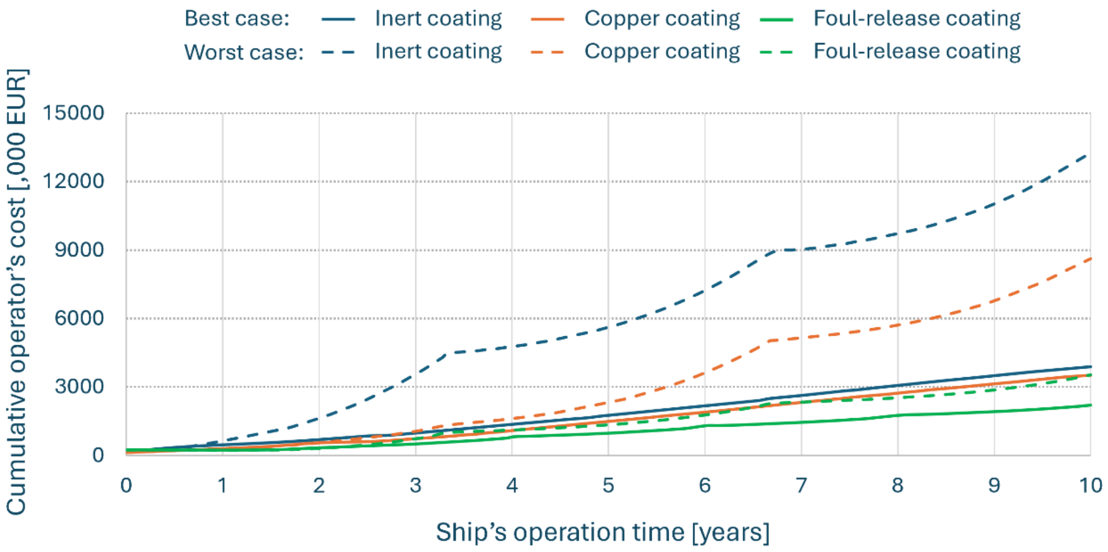


Fig.6: Cumulative operator's costs over time for best and worst scenarios

These findings indicate that the evaluation of the expenses associated with a hull maintenance strategy can vary depending on whether it is considered a short-term or long-term plan. Although there are slight differences depending on the type of coating, in the initial stages, it is difficult for the operator to clearly perceive the effects of hull maintenance. However, as time passes, the cost difference due to maintenance becomes increasingly apparent. In particular, it is important for ship owners to consider this point and establish sustainable long-term plans.

5. Uncertainty factors in cost-benefit analysis

The utilization of HullMASTER and scenario studies in this research involves several limitations and assumptions, which may introduce uncertainties into the cost-benefit analysis outcomes. The efficacy of the coatings used in this study is based on field experiments conducted under idle conditions for approximately one year, considering seawater salinity as a crucial factor affecting biofouling growth and biocide release. It was assumed that periods and seawater conditions other than measured values could be estimated through interpolation and extrapolation. However, the model's sensitivity to the effects and interactions of other factors such as seawater temperature, pH, and lighting conditions at the berthing port may induce additional uncertainty. Not only that, silicone-based foul-release coatings, which remove marine organisms attached to the hull when the ship moves at a certain speed, may have been somewhat conservatively evaluated in this study.

This study did not consider the costs associated with the risk of introducing non-indigenous species due to hull maintenance. However, the operation of ships in the examined region and the transition of ships from outside waters can make it easier for these species to be introduced and spread. Implementing effective hull management measures may reduce the likelihood of non-native species introductions. Furthermore, it was assumed that no distinct wastewater treatment was conducted following in-water hull cleaning in our case studies, leaving room for further review of the potential to reduce toxic substance release from paint particles through a capture system.

The fluctuation in fuel prices, which varies based on the kind of fuel, might introduce uncertainty in the cost analysis results during the life cycle analysis. This study conducted a cost-benefit analysis using the mean LSMGO price from 2020 to 2023, but the range of fuel costs over this period varied by up to five times. Considering that bunker penalties incurred due to hull roughness contribute the most to operational costs, any fluctuations in fuel prices might have a substantial impact on the chosen hull maintenance strategy for the ship.

6. Conclusion

This study employed HullMASTER, a decision-support tool for ship maintenance strategies, to perform a comprehensive cost-benefit analysis of various hull scenarios on the Kattegat and Danish Strait routes. The analysis shows significant differences in increased operating and socio-environmental costs due to biofouling and hull maintenance compared to hydraulically smooth hulls, even on the same ship and route (up to 6 times for operational costs and 7.2 times for socio-environmental costs). It was found that preventing hull roughness increases through hull treatment and in-water hull cleaning at appropriate intervals can reduce bunker penalties and socio-environmental damages such as climate change, human impacts, and ecotoxicity. Out of the three coating types examined, non-biocide foul-release coatings were determined to be the best sustainable choice for the Kattegat and Danish Strait routes. These coatings achieve sustainability by decreasing exhaust gas emissions and limiting the discharge of biocidal pollutants into the ocean.

Moreover, there was a substantial disparity in expenses between the short-term and long-term periods as a result of hull maintenance. Although the cost-effectiveness of hull maintenance may not be immediately apparent, the disparities have become increasingly evident with time. These findings highlight the significance of hull maintenance for ship operators and indicate the necessity of developing sustainable, long-term strategies. Nevertheless, this study is a case study conducted only in the Kattegat-Danish Strait route. The outcomes of the cost-benefit analysis may differ based on factors such as ship characteristics, operational profiles, and operating locations. Future studies will necessitate extensive cost-benefit analysis that considers more diverse factors and a wider range of ship operating conditions and areas.

Acknowledgement

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