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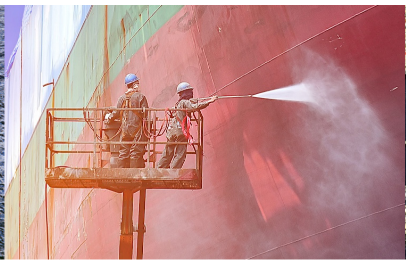
HÅLL 2.0

Demonstration of sustainable ship hull maintenance strategies

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HÅLL 2.0 - Demonstration of sustainable ship hull maintenance strategies

Authors

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Summary

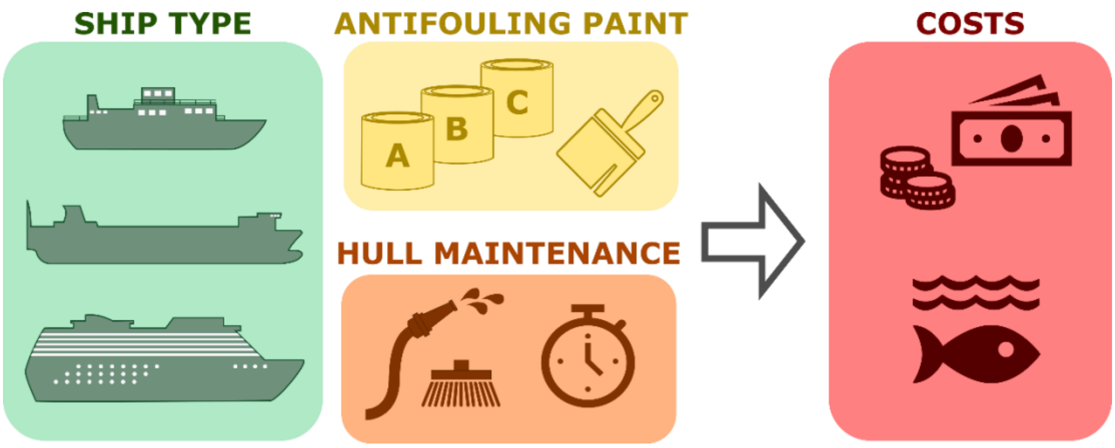
Biofouling, the attachment of organisms like algae and barnacles, increases ship surface roughness, leading to higher fuel consumption, operational costs, and greenhouse gas emissions. Antifouling paints, classified into biocidal, foul release (FR), and biocide-free hard inert coatings, are used to prevent this. Biocidal coatings, mainly copper-based, release biocides affecting non-target organisms. HullMASTER, developed in the HÅLL1 project as a decision-support tool, compares operational and socio-environmental costs of different hull maintenance strategies. Specifically, the model evaluates operational costs (hull cleaning, dry docking, paint application) and social and environmental damage costs (climate change, air quality, marine eutrophication, marine ecotoxicity) based on different hull maintenance strategies. The HÅLL2 project aimed to expand HullMASTER's coverage from the Baltic Sea to European waters, include more antifouling strategies, and assess fouling growth and biocide release in various marine environments.

In the project, we have demonstrated HullMASTER's practical use through full-scale tests, ship performance analysis, stakeholder workshops, and tool updates. HullMASTER comprises three key components: input parameters, models and calculations, and a results section with cost comparisons. Input parameters include vessel specifications, operational profile, and hull maintenance strategy, allowing users to define vessel-specific values. The models and calculation components are based on field tests and XRF analysis of coatings across European waters. It includes a biological fouling model to predict hull roughness penalties and emissions (GHG, NOX, SOX, PM2.5, NMVOC) and a biocide release model for copper and zinc emissions from passive leaching and in-water hull cleaning. The results section enables cost comparisons between different hull maintenance scenarios and a business-as-usual (BAU) scenario. Simulations using HullMASTER identified optimal hull maintenance strategies for RoPax vessels in the Baltic Sea. The best scenarios involved regular gentle in-water hull cleaning (IWHC) and dry-docking intervals, resulting in significant cost savings and reduced environmental impact. The optimal strategy varied by coating type and region, with FR coatings showing excellent antifouling performance and cost savings.

Laboratory tests assessed how water flow affects biocide release rates. Experiments with different coatings and flow speeds were conducted, providing insights into copper release rates and their dependence on ship speed. These results benefit the HÅLL2 project by modeling biocide release and coating lifetime based on ship speed. HullMASTER has been developed based on field test results from three locations along the Swedish coast (HÅLL1 project), seven European port terminals (HÅLL2 project), and additional sites from related antifouling research projects. The model for biofouling growth derived from this

study enables the prediction of overall trends in European waters with similar environmental and coating conditions. Stakeholder engagement has been crucial for HullMASTER's development and validation. Paint manufacturers collaborated on paint selection, application, and test setup. Shipping company DFDS provided insights into hull management practices and in-service performance data, validating HullMASTER's predictions. A workshop in fall 2024 showcased HullMASTER's use and research findings, promoting sustainable shipping practices.

The project has identified key aspects for future HullMASTER updates, including microplastics and non-native species. Incorporating these will enhance HullMASTER's holistic assessment of antifouling strategies and support sustainable hull maintenance strategies.



Sammanfattning

Påväxt av marina organismer på fartygsskrov, som havstulpaner och alger, är ett stort problem som leder till ökat motstånd, högre bränsleförbrukning samt större utsläpp av växthusgaser. För att förhindra påväxt (biofouling) används antifoulingfärger på skrovet. Dessa färger brukat delas in i tre övergripande kategorier: biocidinnehållande färger, foul-release (FR) färger samt biocidfria hårda färger.

Biocidinnehållande färger, där koppar är den vanligaste biociden, påverkar inte bara påväxten på skrovet utan även marint liv utanför skrovet (sk icke-mål organismer). Med beslutsstödet HullMASTER, som utvecklades inom [HÅLL1-projektet](), kan man jämföra kostnader för olika skrovunderhållsmetoder. HullMASTER inkluderar både kostnader för sjöfartsindustrin samt för miljö/samhälle. I HullMASTER utvärderas samhälls- och miljökostnader (som klimatförändringar, luft- och vattenkvalitet) och operationella kostnader (skrovrengöring, dockning och färgapplicering) för olika underhållsstrategier. Inom HÅLL2 har vi skalat upp HullMASTER från att tidigare varit utformat för Östersjön till att inkludera europeiska vatten, samt utökat modellen till att inkludera fler antifoulingfärger och hur skrovet kan underhållas för att ta bort eller förhindra påväxt.

Inom HÅLL2 har vi tagit fram ny data för påväxt och biocidläckage i europeiska vatten och med denna kunskap uppdaterat HullMASTER-Baltic Sea till HullMASTER-Europe. Vidare har vi demonstrerat HullMASTER på workshops med fartygsoperatörer och andra intressenter. Genom tillgång till operationella data från fartyg med olika antifouling-alternativ gör vi en kontinuerlig validering av verktyget.

HullMASTER består av tre delar: indata-parametrar, modellering och beräkningar, samt en resultatdel med kostnadsjämförelser. HullMASTERs användare kan genom att definiera sin fartygsspecifika input (som rutt, underhållsstrategi för skrov som färgval och skrovrengöringsfrekvens) beräkna sina förväntade (och samhällsekonomiska externa) kostnader.

Modellering och beräkningar baseras på fälttester och XRF-analyser av paneler med olika antifouling-produkter som exponerats i europeiska hamnar (terminaler). HullMASTER inkluderar både en modell för att förutsäga betydelsen av påväxten för luftutsläpp (växthusgaser, NOX, SOX, PM2.5, NMVOC) samt en modell för läckage av biociderna koppar och zink, både från passivt läckage och vid skrovrengöring.

I HullMASTERs resultatdel genereras kostnadsjämförelser mellan olika scenarier för skrovunderhåll i förhållande till ett business-as-usual (BAU) scenario baserat på att fartyget använder en kopparfärg utan skrovrengöring. Genom simuleringar med HullMASTER kunde vi i HÅLL2 identifiera optimala

skrovunderhållsstrategier för RoPax-fartyg i Östersjön. Resultaten visade att betydande kostnadsbesparingar och minskad miljöpåverkan kan uppnås genom regelbunden, skonsam rengöring av skrov i vattnet (In Water Hull Cleaning, IWHC) samt val av dockningsintervall. Hur man når en optimal strategi varierar beroende på ruttområde och typ av antifoulingfärg, där foul-release (FR) färger hade mycket god antifouling-prestanda och gav betydande kostnadsbesparingar framför allt för samhället (externa kostnader) men också för redaren i jämförelse med BAU-scenariot.

I laboratorieförsök undersöktes vattenflödets betydelse för biocidernas läckagehastighet. Genom experimentella studier med olika flödeshastigheter och antifoulingfärger genererades data för att förklara hur läckagehastighet av koppar är beroende av fartygets hastighet.

Genom att modellera läckage av biocider samt kunskap om fartygets hastighet kan man förutspå färgens livslängd. HullMASTER inkluderar resultat från fältförsök gjorda på tre platser längs den svenska kusten (HÅLL1-projektet), sju europeiska hamnterminaler (HÅLL2-projektet) och ytterligare platser från pågående forskningsprojekt med fokus på antifouling.

Med hjälp av påväxtmodellen som utvecklats inom HÅLL2 kan man förutspå övergripande trender för olika antifouling-alternativ i europeiska vatten.

Intressenternas/användarnas engagemang har varit avgörande för HullMASTERs utveckling och validering. Vi har inom HÅLL2 etablerat samarbete med marknadens stora färgtillverkare/producenter och diskuterat färgval, applicering och utförande av försök. Genom ett etablerat samarbete med rederiet DFDS har vi fått både information och erfarenhet (studiebesök i torrdocka) kring skrovunderhållsmetoder. Vidare har DFDS tillhandahållit prestandadata för fartyg i drift, vilka används för validering av HullMASTERs modelleringar. Under en workshop i november 2024 demonstrerades HullMASTER och våra senaste studier och resultat inom antifouling-forskning.

Slutligen har vi inom HÅLL2 kartlagt behovet av data/information/kunskap inför framtida uppdateringar av HullMASTER med exempelvis mikroplaster och främmande arter. Genom att inkludera dessa parametrar kommer HullMASTER kunna utföra mer holistiska bedömningar av antifouling-strategier och därigenom bli ett ännu mer robust verktyg för att identifiera hållbara skrovunderhållsstrategier.

Contents

1 Introduction

The attachment of fouling organisms, such as algae, barnacles, and mussels, poses a significant challenge for the shipping industry. This so-called biofouling increases the roughness of the ship's surface, leading to higher hydrodynamic friction. As a result, fuel consumption rises, operational costs for ship operators accelerate, and there is an increase in greenhouse gas emissions and other pollutants affecting climate, human health and the environment (Yebra et al., 2004). The most common method to prevent biofouling is to coat the hull with antifouling paints. These paints are generally classified into three categories: (i) biocidal antifouling coatings, (ii) foul release (FR) coatings, and (iii) biocide-free hard inert coatings.

Biocidal antifouling coatings use around 25 different biocides globally, with inorganic copper species being the most prevalent, found in nearly 80% of these coatings (Paz-Villarraga et al., 2022). They all function by releasing biocides from the paint surface to the surrounding water which could affect also non-target organisms and ecosystems. As an example, copper-based antifouling paints has shown to be the largest anthropogenic source, accounting for one third of the total input of copper, to the Baltic Sea (Ytreberg et al., 2022). FR coatings work by minimizing the adhesion force between the coating surface and fouling organisms and can be either biocide-free or contain biocides. Hard inert coatings are typically used on vessels operating in icy conditions and are often combined with mechanical cleaning systems (Weber and Esmaeili, 2023). It is also common practice to perform proactive cleaning on both biocidal antifouling coatings and FR coatings, despite manufacturers' advice against it due to potential damage to the coating system.

An effective antifouling strategy is crucial for both ship operators, due to fuel savings, and society, as it helps reduce greenhouse gas emissions and other atmospheric pollutants. However, balancing this strategy to ensure that the paints do not negatively impact the marine environment is very challenging for both ship operators and regulators. To assist the shipping industry in making sound decisions on antifouling strategies that are both economically feasible and environmentally friendly, we created the decision support tool HullMASTER. This tool was developed during the HÅLL1 project (2019-2021), funded by Trafikverket and Lighthouse. However, HullMASTER was initially limited to the Baltic Sea and based on only three coatings: one copper-based coating, one biocide-free foul release (FR) coating, and one inert coating without antifouling properties.

The main outcome of HÅLL1 was the development and demonstration of HullMASTER. However, no analysis on optimal hull maintenance strategies in the Baltic Sea was performed. For the tool to be used more extensively, its geographical scope should be expanded to cover all (or most) European sea basins.

1.1 Aims and structure of the report

Main objectives

In our previous research project HÅLL1 (2019-2021), we developed HullMASTER, a prototype designed for the performance and impact assessment of various hull coating types and maintenance activities (refer to Oliveira et al., 2022). HullMASTER serves as a guiding tool for the shipping industry and environmental authorities focusing on the sustainability of hull maintenance strategies. The results from the tool are presented in terms of cost savings for operators (maintenance and fuel costs) and associated socio-environmental damage costs (climate change, health and marine water quality).

The main objectives of the follow-up project, HÅLL2 (2023-2024), were to broaden the geographical coverage of the tool from the Baltic Sea to European waters to incorporate more anti-fouling paint strategies and to assess the impact of different marine environments on biocide release rates. Additionally, we have showcased the practical application of HullMASTER through full-scale demonstration of evidence-based approaches, comprehensive ship performance analysis, hands-on workshop training with stakeholders, and continuous updates of the tool (see **Figure 1**).

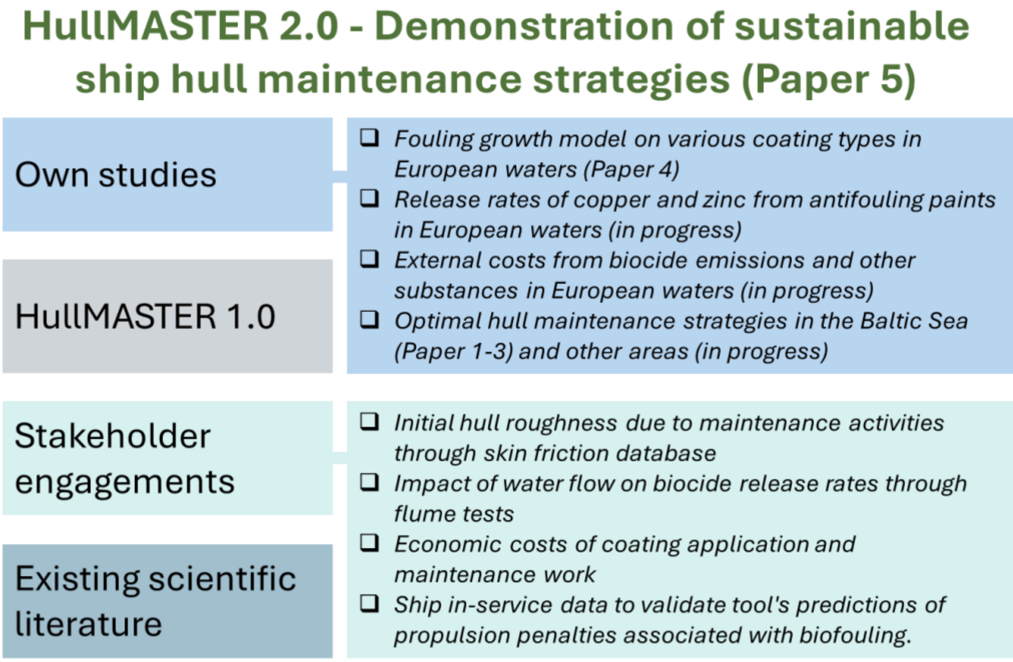


Figure 1*. Main sources of information used to fill knowledge gaps and expand HullMASTER into European waters. For the list of papers, refer to* ***Table 1****.*

Knowledge gaps and specific aims

Based on the knowledge gaps identified during the HÅLL1 project and a thorough review of the scientific literature, we identified the following areas that need to be addressed to enhance HullMASTER for European waters:

i. Measurements of copper release rates from commercial antifouling paints exposed in various European sea basins.
ii. Prediction of biofouling growth on different coating types across diverse European sea basins.
iii. Calculation of external costs due to the emissions of biocides and other substances of concern in European waters.
iv. Identification of optimal sustainable hull management strategies tailored to different vessel operating profiles and environmental conditions.

To fill these knowledge gaps, the project launched field tests at seven European port terminals in collaboration with the shipping company DFDS to evaluate the efficacy of different antifouling coatings in preventing biofouling. The ports included in this project are as follows, with the experiment lasting approximately 12 months.

- Copenhagen, Copenhagen (55.70N, 12.59E)
- Sweden, Gothenburg (57.69N, 11.84E)
- Netherlands, Vlaardingen (51.90N. 4.36E)
- Belgium, Ghent (51.11N, 3.76E)
- United Kingdom, Immingham (53.64N, -0.20E)

- Italy, Trieste (45.64N, 13.74E)
- Turkey, Pendik (40.86N, 29.27E)

The following hull coating types have been tested, and their associated emissions and costs are modelled in HullMASTER.

- a traditional biocidal copper coating
- a biocide-free silicone foul-release coating
- a biocidal silicone foul-release coating
- a biocide-free inert coating

Structure of the report

Section 2 summarizes the methodology used to address these knowledge gaps in relation to modelling of HullMASTER. Following the field tests, we focused on developing a prediction model for biofouling growth on different coating types across various European sea basins over static time to estimate the energy penalty, greenhouse gas (GHG), nitrogen oxides (NO_X), sulphur oxides (SO_X), fine particulate matter (PM2.5) and non-methane volatile compounds (NMVOC) emissions from ships due to biofouling and hull maintenance activities involving these coatings (refer to Section 2.2; Paper 4). Next, we used XRF methodology (Lagerström and Ytreberg, 2021) to measure the actual amount of copper released from several antifouling paints and developed a model to estimate copper release rates based on different environmental conditions and coating properties (refer to Section 2.2).

The subsequent section of this report (Sections 3.1–3.4) describes the development and demonstration of HullMASTER (version 2.0), stakeholder engagement and interaction, and future directions for HullMASTER as they relate to the specific objectives of this report, including specifically:

- Enhancing a decision-support tool for sustainable hull maintenance (HullMASTER) through novel data on alternative paint/solutions, expanded geographical scope, and increased confidence in evidence of savings/expenses related to maintenance (Section 3.1; Paper 5)
- Engaging stakeholders in developing and use of HullMASTER (Section 3.2-Section 3.4)
- Deriving an optimal hull maintenance strategy for vessels operating in the Baltic Sea region using the existing tool (Section 3.5; Papers 1-3)
- Identifying limitations of current findings and outlining future development of HullMASTER (Section 3.6)

More detailed and comprehensive analyses than those summarized in each section are available in the relevant scientific deliverables listed in **Table 1**. Additionally, an extensive description of the tool itself and its user manual will be provided here https://research.chalmers.se/en/publication/527711.

Table 1. *Scientific deliverables that have resulted from the HÅLL2 project and are described in this report.*

Paper	Title	Status
1	Kim, Y., Lagerström, M., Granhag, L., & Ytreberg, E. (2025). Sustainable Hull maintenance strategies in Baltic Sea region through case studies of RoPax vessels. Marine Pollution Bulletin, 211, 117453. https://doi.org/10.1016/j.marpolbul.2024.117453	Published
2	Kim, Y., Lagerström, M., Granhag, L., & Ytreberg, E. (2024). Cost-Benefit Analysis of Ship's Hull Maintenance Scenarios in the Kattegat and Danish Strait Route. 9th Hull Performance & Insight Conference, HullPIC'24, 140-148. https://research.chalmers.se/publication/544561/file/544561_Fulltext.pdf	Published
3	Granhag, L., Lagerström, M., Kim, Y., Oliveira, D., Larsson, A., Leer-Andersenm, M., Werner, S., & Ytreberg, E. (2023). Towards sustainable ship hull maintenance strategies: Focus on biocide-free silicone foul-release coatings. Poster presented at International Antifouling Conference; Sep 12-13, 2023; Gothenburg, Sweden.	Presented
4	Kim, Y., Lagerström, M., Granhag, L., & Ytreberg, E. (2025). Mapping Biofouling Intensity and Modeling Antifouling Coating Efficacy for Sustainable Ship operations in European Waters.	In preparation
5	Kim, Y., Lagerström, M., Granhag, L., & Ytreberg, E. (2025). A tool for comprehensive assessment of the cost and environmental impact of hull maintenance strategies for ships operating in European waters.	In preparation

2 Identified knowledge gaps regarding modelling and how they were solved

2.1 Efficacy of different hull coatings in different European Sea basins

To implement a fouling growth model that takes into account the different marine environments and biological fouling dynamics in European waters, we used field tests data conducted at different ports and with different coating types, as shown in **Table 2** and **Table 3**. Each paint product was applied to four PVC panels that were statically submerged in water (depth 1-2 m) for the duration of the experiment. The surface condition of each panel was monitored monthly, and the fouling condition was quantified using the NSTM fouling rating scale (US Navy, 2006).

Table 2. *Types of commercial paint products used in the HÅLL2 project and their content of the active substances.*

Coating type	**Product**	**Cu2O (wt%, ww)**	**ZnO (wt%, ww)**	**CuPT (wt%, ww)**	**ZnPT (wt%, ww)**	**Dcoit (wt%, ww)**
Traditional biocidal copper coating	P1	25-50	10-25	-	-	-
	P2	20-30	1-5	1-5	-	0.1-1
Biocide-free silicone foul-release coating	P3	-	-	-	-	-
	P4	-	-	-	-	-
Biocidal silicone foul-release coating	P5	-	-	5-10	≤0.18	-
Biocide-free inert coatings	P6	-	-	-	-	-

Table 3. *Details about the location, period, and products tested for field tests.*

Location	**Test period**	**Product**
Copenhagen	2023/10-2024/10	P1, P2, P3, P4, P5, P6
Gothenburg	2023/07-2024/07	P1, P2, P3, P4, P5, P6
Vlaardingen	2023/08-2024/08	P1, P2, P3, P5, P6
Ghent	2023/10-2024/10	P1, P2, P3, P4, P5, P6
Immingham	2023/07-2024/07	P1, P2, P3, P5, P6
Trieste	2023/07-2024/07	P1, P2, P3, P4, P5, P6
Pendik	2023/10-2024/10	P1, P2, P3, P4, P5, P6

Studies conducted in the Baltic Sea have shown that cumulative idle time and salinity are the two main parameters that influence the fouling growth rate (Oliveira and Granhag, 2020; Wrange et al., 2020). As shown by the blue line in **Figure 2**, the existing HullMASTER model predicts the fouling growth rate on the hull surface as a function of cumulative idle time during ship operations (Oliveira et al., 2022). This assumption was valid when we expanded our coverage area from the Baltic Sea to European waters. In addition, to account for seasonal variations in fouling growth rates, we included a seasonal effect term based on periodic temperature variations in the form of a cosine function, shown by the orange line in **Figure 2**.

Other environmental factors may also affect fouling growth rate and intensity, but some variables are difficult to obtain and there may be significant uncertainty in the data. Therefore, for the practical application of this model, we focus only on the parameters of accumulation time, salinity, and temperature. The monitored data from the field test and the predicted results using the fouling growth model are shown in **Figure 3**.

Fouling growth rate models in HullMASTER were implemented for each location and coating type. If fouling growth rates need to be estimated at an arbitrary location, one could adopt one of the fouling growth rate models for nearby locations or similar environments for the different locations presented in this study, or perform linear interpolation for salinity based on the fouling growth rate model for the closest salinity environment (default setting in HullMASTER).

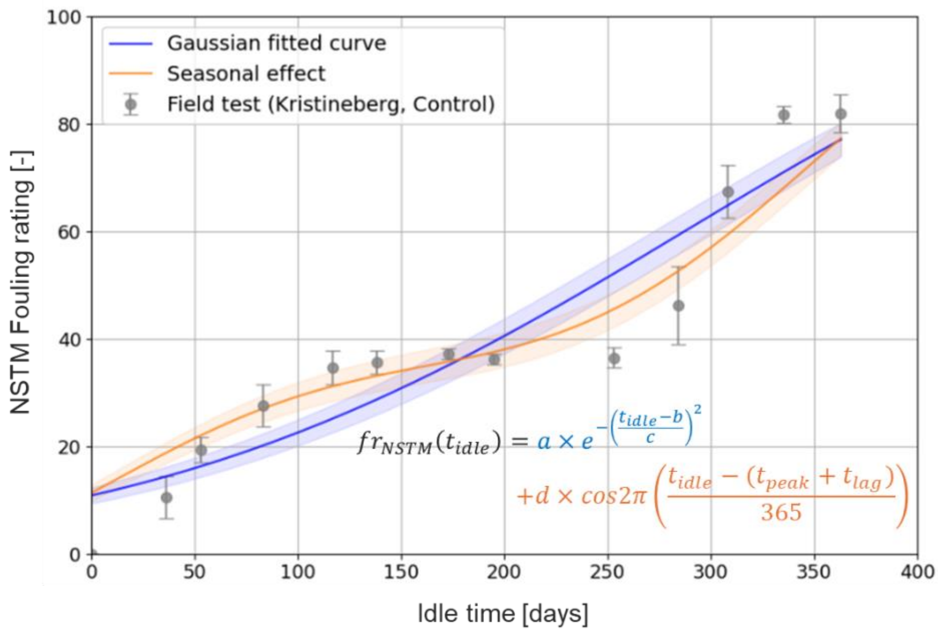


Figure 2. *Fouling growth rate prediction model as a function of idle time (example of biocide-free inert coating at Kristineberg).*

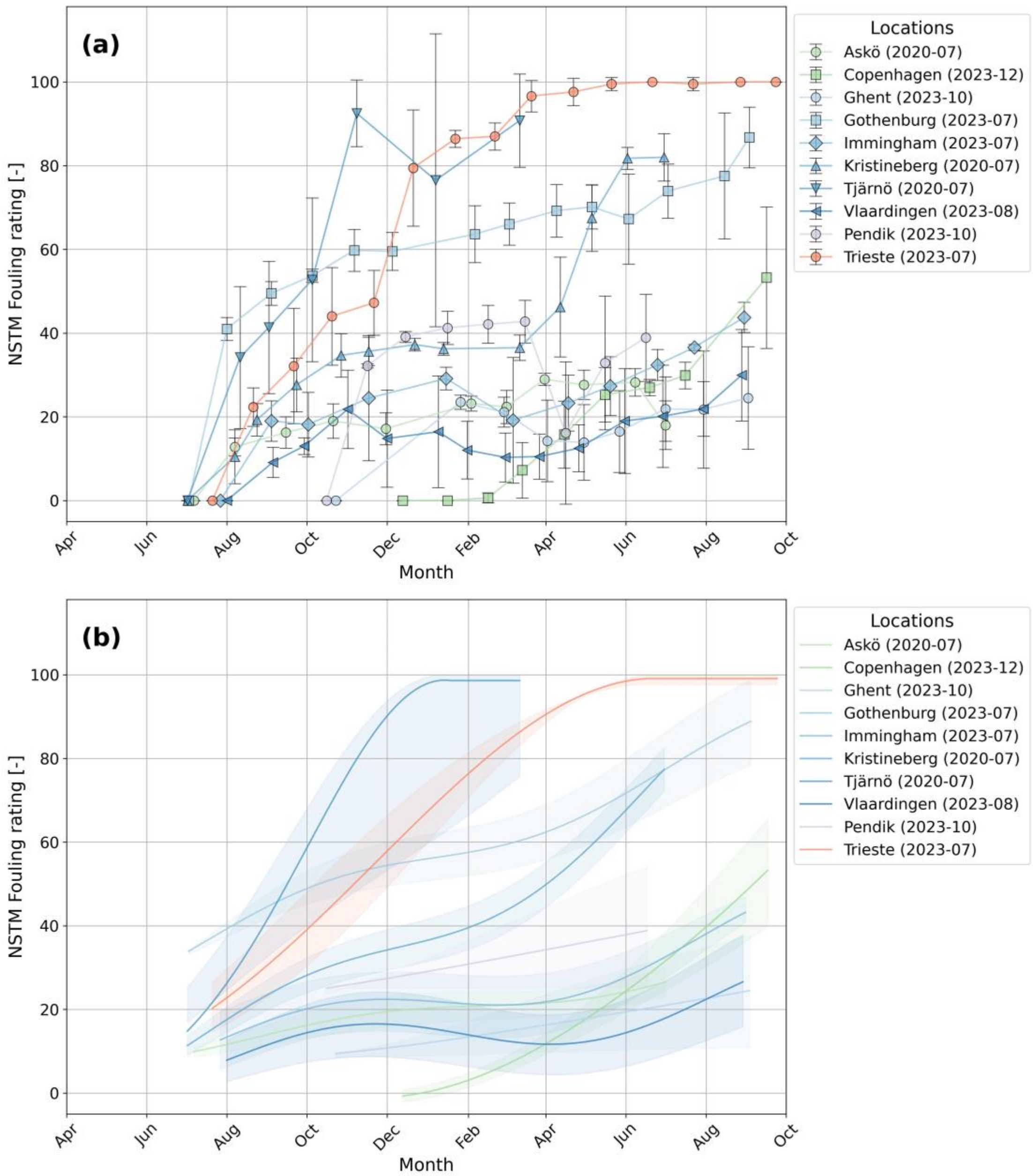


Figure 3. *Time series NSTM fouling ratings for panels with biocide-free inert coatings: (a) monitoring data from field tests, (b) prediction from fouling growth model.*

2.2 Release rates of biocides in different European Sea basins

Release rate measurements were performed on two traditional biocidal copper coatings and one biocidal silicone foul-release coating containing copper pyrithione (CuPT) and zinc pyrithione (ZnPT) utilizing the XRF method developed by Lagerström and Ytreberg (2021). Since the field experiments concluded just a few months before the project ended, we are still processing the data. These release rate measurements will be included in the next version of HullMASTER and presented in Paper 5. However, the current version of

HullMASTER uses a release rate method developed for salinities up to 26 PSU, making the model applicable in estuary environments such as the largest ports in Europe, e.g., the Port of Rotterdam and the Port of Amsterdam.

3 Development and demonstration of HullMASTER

3.1 Development of HullMASTER including an overview of required input data, main assumptions, and modelling concepts

Overview of HullMASTER

HullMASTER consists of three essential components: input parameters, models and calculations, and results section including cost comparisons (see **Figure 4**). Input parameters include vessel specifications, operational profile, and hull maintenance strategy, and users can define vessel-specific values for all parameters in addition to the default values.

The second component, models and calculations, is based on the results of field tests and XRF analysis of different coatings conducted across European waters. As covered in Sections 2.1–2.2, the biological fouling model is used to predict hull roughness penalties and relevant emissions to the atmospheric (GHG, NO_X, SO_X, PM2.5 and NMVOC) and marine environments, and it includes a biocide release model that calculates the marine environmental emissions of copper and zinc resulting from passive leaching and in-water hull cleaning.

The final component enables a cost comparison between different hull maintenance scenarios and a business-as-usual (BAU) scenario. The assessment includes four main social and environmental damage costs: climate change, air quality (human health), and marine eutrophication related to ship energy penalties, and marine ecotoxicity resulted from antifouling coatings; and operational costs of hull cleaning, dry docking, paint application, etc. derived from stakeholder engagement from a variety of sources, including shipowners, paint manufacturers and shipyards.

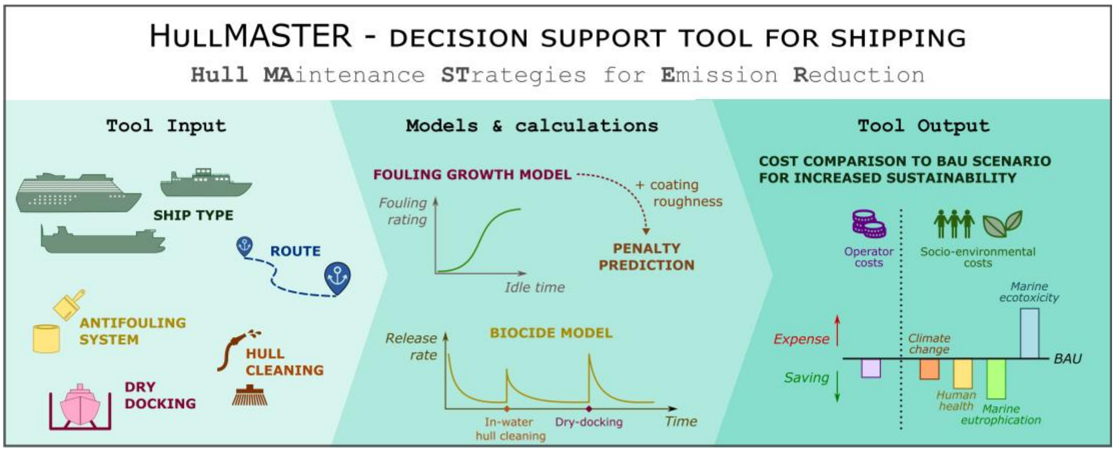


Figure 4. *Overview of HullMASTER and the three main components; tool inputs, models and calculation and tool output.*

Development status of HullMASTER

HullMASTER has been developed as a decision-support tool that enables the comparison of operational costs and external costs associated with socio-environmental damage impacts between different hull maintenance strategies, developed in the HÅLL1 project. HullMASTER was implemented using Matlab® App Designer (version R2019b) and is available as a standalone Windows application. The focus of the HÅLL2 project was to enhance the reliability and accuracy of the existing tool by incorporating diverse input data and expanding its applicability to European waters. For detailed updates on specific modules in the new version compared to the existing tool, please refer to **Table 4**.

Table 4. *Summary of HullMASTER updates. The details shown for HullMASATER 2.0 in the table are in addition to and inclusive of existing models or data from HullMASTER.*

Item	HullMASTER	HullMASTER 2.0
Biofouling growth	▪ Field tests at 3 locations along Swedish coast ▪ 4 commercial paint products ▪ Fouling growth model based on idle time, salinity in Baltic Sea	▪ Field tests at 7 locations in European waters ▪ 6 commercial paint products ▪ Fouling growth model based on idle time, salinity, temperature (seasonality) in European Sea
Emissions to water & air	▪ Copper and zinc release rates (sailing/IWHC) ▪ GHG emissions based on 4th IMO GHG study	▪ Updated copper and zinc release rates (Sailing/IWHC/DD) based on more scientific papers and field test data in European waters (in progress) ▪ Microplastic release based on scientific literature (in progress) ▪ Risk of invasive species (in progress) ▪ GHG emissions based on 4th IMO GHG study
Ship energy penalty & validation	▪ Validation using 9 vessels' operation data	▪ Validation using 2 additional vessels' operation data (in progress)
Cost estimates	▪ Bunker prices for 3 consecutive years (2017-2020) ▪ Hull maintenance costs in Baltic Sea ▪ Socio-environmental damage costs	▪ Bunker price for 3 consecutive years (2021-2024) ▪ Hull maintenance costs in European Sea scale ▪ Socio-environmental damage costs in European Scale

3.2 Stakeholder engagement in HullMASTER development

Paint manufacturers

Stakeholder engagement has been crucial for both the development and validation of HullMASTER. The selection of paints, their application to test panels, and the overall test setup were conducted in collaboration with paint manufacturers A and B (anonymized). During and after the test period, the antifouling efficacy results of each coating at various test locations and environmental conditions were shared with paint manufacturers to promote transparency and sustain their interest in the research.

Shipping company

Shipping company DFDS collaborated on the installation of the coated panels at their ports and facilitated the regular monitoring of biofouling status on these panels by terminal staff during the testing phase.

They also provided valuable insights into their hull management practices and provided in-service performance data on their vessels, which was used to validate

HullMASTER's predictions regarding the propulsion penalties associated with biofouling. The validation of the tool using these vessel data will be included in the next version of HullMASTER and presented in Paper 5

Additionally, we conducted a site visit during the maintenance of DFDS vessels at Odense Fayard Drydock. This visit allowed us to assess hull fouling conditions firsthand and gather practical information on maintenance strategies, i.e., hull surface preparation including hull cleaning and spot/full blasting, coating lifetime, repainting frequency, thickness of applied coating layers, etc.

Workshop in autumn 2024

In the autumn of 2024, we organized a workshop titled "Latest Antifouling Research focus on Sustainable Shipping". During this event, we presented the utilization and demonstration of HullMASTER along with our research findings. Approximately 40 stakeholders from academia, industry, governmental authorities, and public organizations participated in the workshop, both online and in-person. The exchange of insightful ideas and the encouragement of using HullMASTER are expected to promote sustainable shipping practices, which will contribute to "Hållbar sjöfart/Sustainable shipping".

Other stakeholder engagements

During the project, other stakeholders, such as Lloyd's Register, reached out to us to discuss the applicability of HullMASTER for their register and classification services of antifouling coatings. Additionally, competent authorities in Sweden, including the Swedish Transport Agency, contacted us to discuss submission documents describing the HullMASTER tool to IMO subcommittees such as MEPC and PPR, as well as to the regional sea conventions HELCOM and OSPAR.

3.3 Flume test to assess how water flow affects release rates of biocides

Copper release rates from coatings are significantly influenced by factors such as speed, salinity, pH, and temperature. Experiments were conducted in laboratory settings to assess the effect of coating type and flow speed on cupper release rates. In addition, two test methods were compared, flow exposure in a flume using filtered (50µm) high-salinity seawater and flow exposure on a rotary cylinder in artificial seawater matching the natural seawater salinity.

Three types of coating were used in the experiments, all containing cuprous oxide as the primary active ingredient. The coatings included two commercial formulations designed for leisure boats with different leaching rates and one commercial coating intended for larger vessels. These coatings were selected to represent commonly used products while also identifying potential uncertainties in the testing procedure. Each coating panel was marked with 12 measurement points, and XRF analysis was performed on each point before and after immersion to determine copper loss.

In the flume, panels of the same coating type were placed 3 in a row downstream of each other on a plastic plate flush to the flume floor (**Figure 5**). The coatings were exposed to 0.7 m/s in 4 days. Panels were also statically immersed with one panel of each coating type exposed for 4 days and another set of panels for 10 days. A previous flume study also investigated the steepness of the boundary layer and the diffusive boundary layer thickness, which will be used to understand the mechanisms behind differences in leakage rates among coating types.

In collaboration with the Danish University of Technology, the same coating types were also tested on a rotary cylinder using artificial seawater with two dynamic flow exposure types running at 5.14 m/s and 7.72 m/s as well as the static immersions for comparison. Results are not yet fully analyzed but subsequently data from the flume and rotary cylinder experiments can be extrapolated to generate a copper release rate curve as a function of speed. These results are expected to provide valuable insights for the maritime sector by demonstrating how copper release is affected by ship speed. For the HÅLL2 project, these results would benefit in modelling the amount of biocide released to the environment but also the lifetime of the coating based on the ship speed.

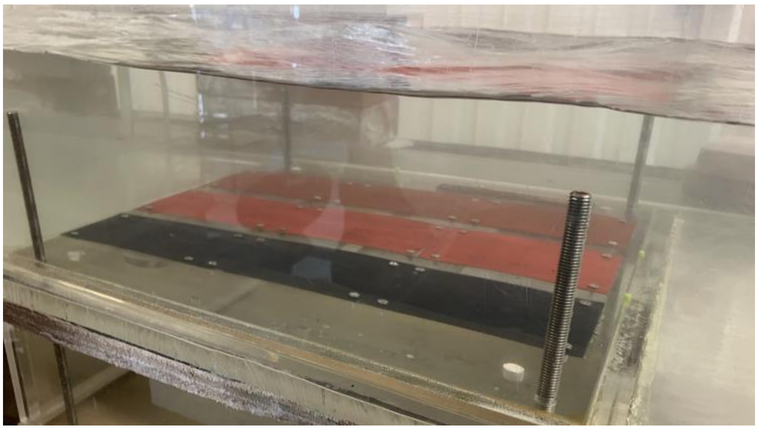


Figure 5. *Panels with three different antifouling coatings mounted and exposed to 0.7 m/s in the flume at Tjärnö Marine Laboratory, University of Gothenburg. The content of copper was measured before and after flow exposure using XRF to calculate release rates.*

3.4 Optimal hull maintenance strategies in the Baltic region.

In Paper 1, we utilized the existing HullMASTER, developed with a focus on the Baltic Sea, to demonstrate actual ship cases and prove the applicability of the tool in decision-making to reduce the social and environmental damage in shipping. Here, we focused on the case of RoPax vessels operating in the Baltic Sea region to identify optimal sustainable hull management strategies. To achieve this, we conducted simulations using HullMASTER, implementing 93 different hull maintenance scenarios for four RoPax vessels over a 10-year operational period (see **Figure 6** and **Figure 7**). The simulation results allowed us to perform a cost-benefit analysis from an economic, social, and environmental perspective of different hull maintenance scenarios in the Baltic Sea region, and it showed the cost savings that could be achieved by adopting the optimal scenario compared to the baseline scenario (see **Figure 8**).

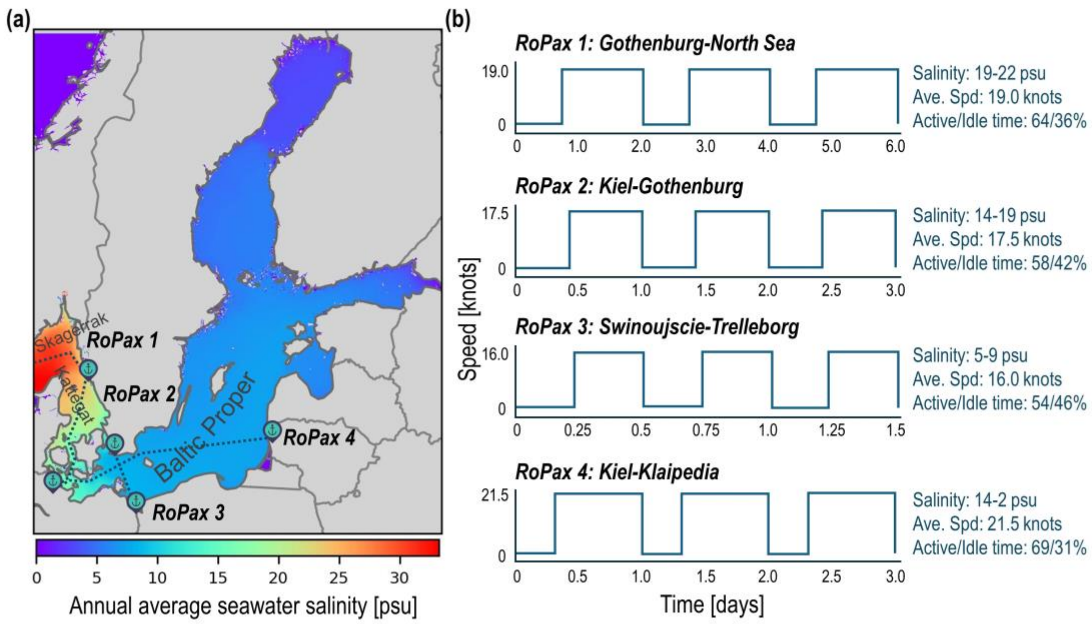


Figure 6. Routes and operational profiles of RoPax vessels in the Baltic Sea used in this study.

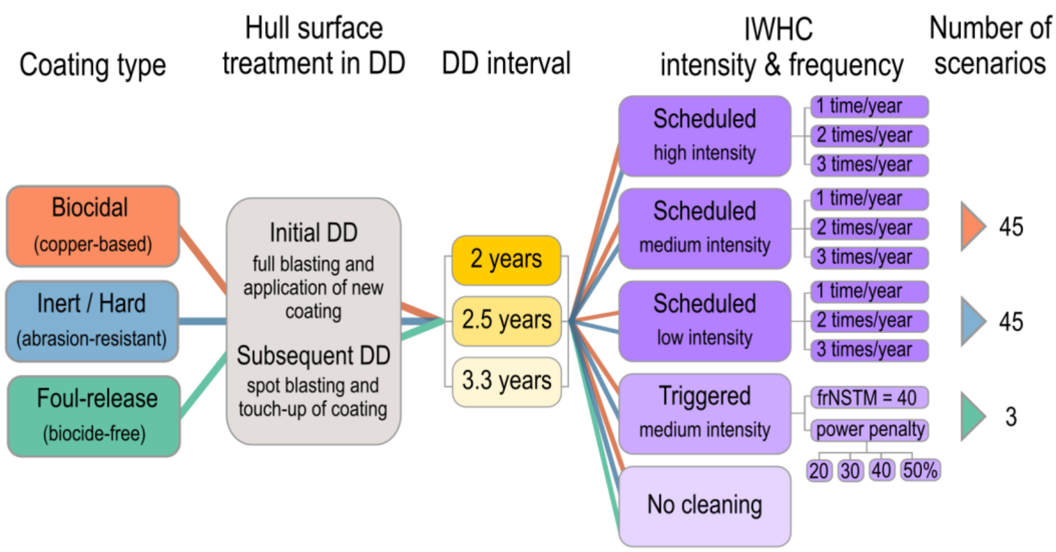


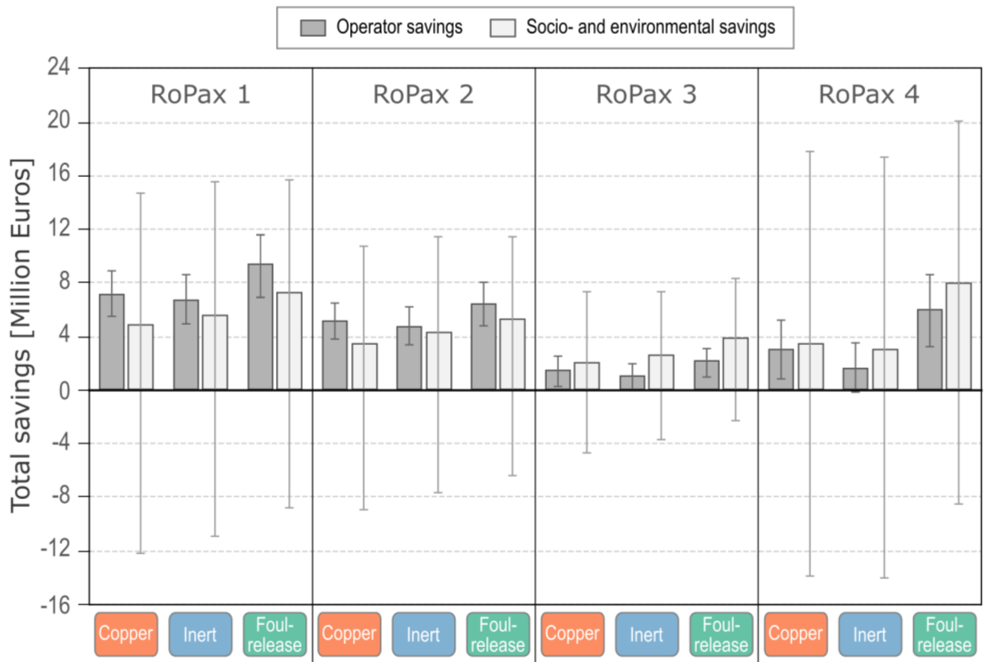
Figure 7. Hull maintenance scenarios simulated in HullMASTER.

Table 5 lists which of the analyzed scenarios would result in the most cost savings while minimizing environmental damage for each ship case and coating type, and **Figure 8** shows the cost savings that could be achieved by adopting these scenarios. The optimal scenario for inert and copper coatings is to perform soft cleaning two to three times a year and one to two times a year, respectively, while maintaining a dry-docking interval of 3.3 years. Inert coatings require more frequent cleaning compared to copper coatings due to their lack of antifouling properties.

Differences in cleaning frequency were also observed between the Skagerrak/Kattegat region and the Baltic Proper region. These results indicate that delaying dry docking with regular gentle IWHC can provide economic benefits for the ship operator while reducing environmental impact. Conversely, foul-release coatings have demonstrated excellent antifouling performance, which can significantly reduce overall operating costs despite the relatively high cost of paint application. The best strategy for foul-release coatings is to reduce the dry-docking interval to two years; however, the difference in cost savings between scenarios is not significant when considering the accumulation of costs over 10 years.

Table 5. *The best practices by ship and coating type among hull maintenance scenarios analyzed in the 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



	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

Savings allocation (%): expense | saving — 0, 25, 50, 75, 100

Figure 8. *Cost-benefit analysis results and detailed savings breakdown of the best-case scenario compared to the baseline scenario. Here, costs are cumulative over 10 years; baseline scenario is a copper coating case with a dry-docking interval of 3.3 years and no IWHC.*

For operating costs, the average savings over a 10-year ship operation scenario range from €2.1 million to €9.3 million for foul-release coatings as compared to the baseline scenario (copper coating, with no IWHC and dry-docking interval of 3.3 years). For copper coatings and inert coatings, savings ranged from €1.4 million to €7.1 million, and €0.9 million to €6.7 million, respectively, in the best practice scenarios as compared to the baseline scenario. The main driver of these cost savings is the reduction in fuel consumption, which significantly outweighs the hull maintenance costs.

In terms of socio-environmental costs, the average savings (compared to the baseline scenario) are €3.8 million to €7.9 million for foul-release coatings, €2.6

million to €5.6 million for inert coatings, and €2.0 million to €4.8 million for copper coatings. For RoPax 1 and RoPax 2 operating in the Skagerrak and Kattegat regions, effective hull maintenance can significantly reduce socio-environmental costs, especially those related to human health and climate change. Conversely, for RoPax 3 and RoPax 4 operating in the Baltic Sea region, the best hull management scenario can contribute to a significant reduction in marine eutrophication damage due to nitrogen (N) deposition, which accounts for the largest share of socio-environmental costs. The estimated damage is calculated only for the amount that exceeds the maximum allowable input for nitrogen in the region, as defined in the Baltic Sea Action Plan (BSAP) by HELCOM for the entire Baltic Sea and its sub-basins.

3.5 Limitations and Future development of HullMASTER

HullMASTER has been developed based on field test results from three locations along the Swedish coast (HÅLL1 project), seven European port terminals (HÅLL2 project), and additional sites from related antifouling research projects. The model for biofouling growth derived from this study enable the prediction of overall trends in European waters with similar environmental and coating conditions (soon to be updated with a new biocide release rate model). However, as illustrated in **Figure 9** depicting fouling intensity based on existing scientific literature and our research findings, fouling intensity varies by region and location. Thus, there are limitations in applying the tool to specific environmental conditions and paint products not covered in the study (e.g., scaling up to a global level or incorporating newly developed paint products). In the future, more field tests in different regions will allow us to improve the tool's coverage and enable the optimization of tailored hull management strategies for vessels.

In addition, estimates based on limited data regarding fouling growth rates, hull roughness, and damage costs carry inherent uncertainties that propagate through the analysis, thereby increasing the uncertainty of the cost-benefit analysis results. Further data collection and related research will be necessary in the future to mitigate these uncertainties.

Furthermore, future developments will investigate a range of impacts associated with hull maintenance, including microplastics and non-native species not yet reflected in the tool, and will include exploring fouling detachment and biocide release rates under dynamic conditions. Incorporating these factors into HullMASTER will enhance its applicability and reliability, ultimately contributing to more sustainable ship hull maintenance strategies.

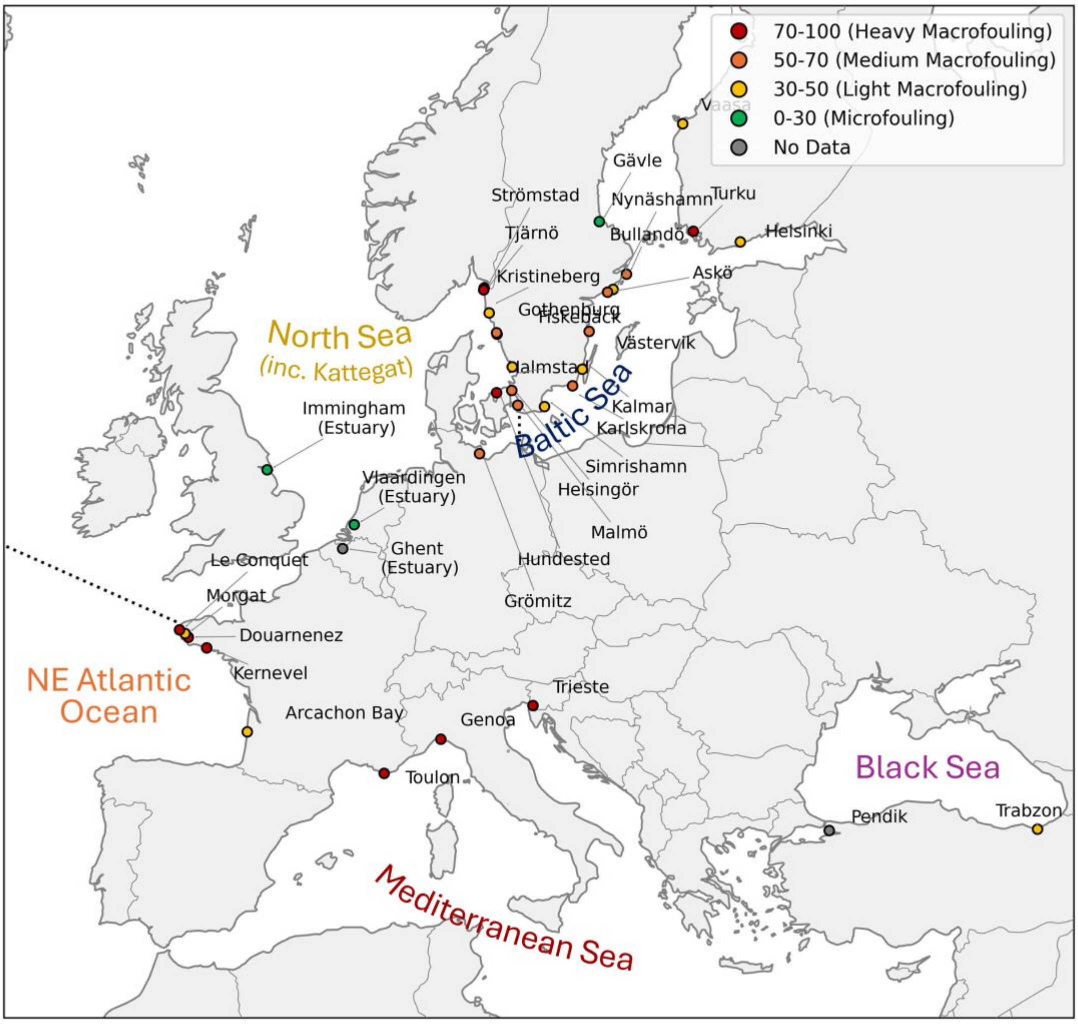


Figure 9. *Biofouling intensity in European waters based on field tests. The fouling intensity at the different locations shown in the figure is the result of post-processing and converting several publicly published papers and reports into NSTM fouling ratings based on our own collected and established criteria.*

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