LIGHTHOUSE
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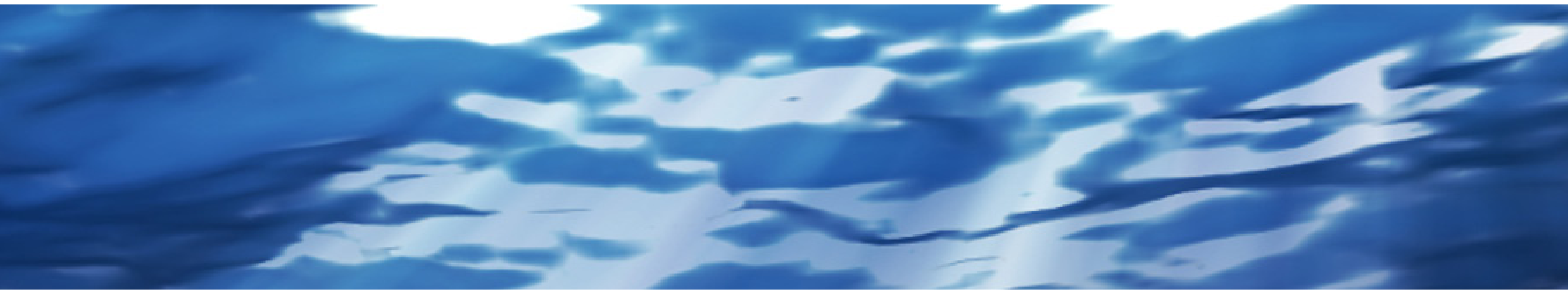

LIGHTHOUSE REPORTS

Sustainable ship hull maintenance strategies

The development of a decision support tool and sustainability classification of antifouling strategies

A research project carried out within the Swedish Transport Administration's industry program Sustainable Shipping, operated by Lighthouse, published in March 2022

TRAFIKVERKET

Sustainable ship hull maintenance strategies through the development of a decision support tool and sustainability classification of antifouling strategies

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Summary

International shipping plays a vital role in the world's transport system and provide socio-economic benefits for the society. However, shipping is also an activity responsible for a range of emissions, e.g., greenhouse gases, air pollutants, and chemical substances, impacting air quality, human health, and the marine environment. In particular, the marine growth (biofouling) on underwater surfaces of a ship hull affects the ship's energy efficiency, leading to propulsion powering penalties which can be translated to increased fuel consumption, air emissions and costs for the shipowner. Measures to control biofouling, using biocidal antifouling coatings and in-water hull cleaning, are however associated with impacts on the marine environment.

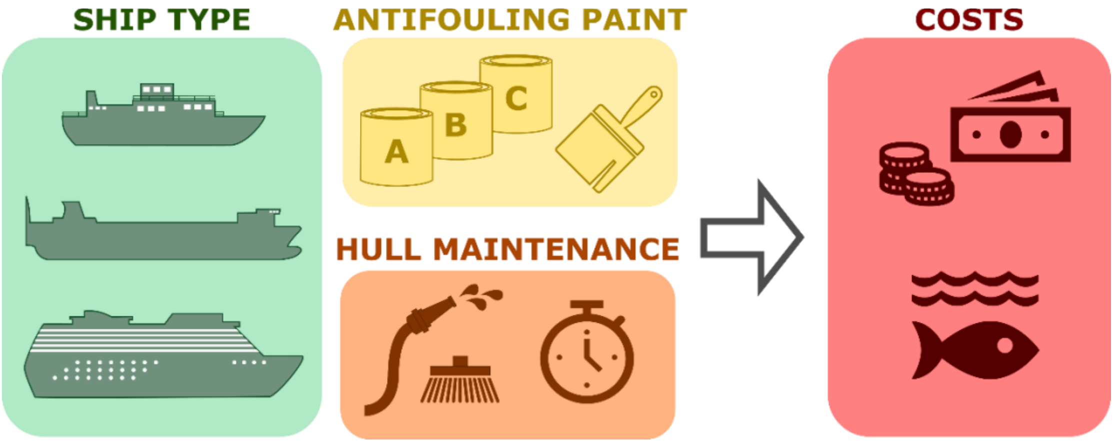
Determining the quantities and types of emissions from a vessel is highly complex. These will depend on the selected hull coating and its associated maintenance, as well as engine specifics, fuel choice and types of exhaust abatement systems. The emissions will also be contingent on the vessel route, as the intensity of hull fouling varies geo-graphically (impacting air emissions and fuel consumption) while biocide emissions from antifouling coatings depend on salinity (impacting water emissions). As a result, optimum hull maintenance strategies to minimize environmental emissions need to be determined for specific vessels and routes. In this project report, we present a standalone cost calculation tool, HullMASTER (Hull MAintenance STrategies for Emission Reduction), specifically developed for this intricate task.

In HullMASTER, developed models simulate the emissions to water and air associated with user-defined hull maintenance scenarios for ships and routes in the Baltic Sea region. A region-specific fouling growth model, based on field data from the Baltic Sea, has been implemented to predict the powering penalty of modelled vessels due to hull fouling. The model has been validated against in-service performance using data from 9 ships (40 vessel-years) operating in the Baltic Sea region with very good agreement. Based on the simulated emissions, HullMASTER calculates the differences in health- and environmental damage costs between scenarios. These are presented alongside the economic cost for operators (i.e., paint application and maintenance costs, increased energy-consumption costs due to biofouling and in-water cleaning costs) in order for shipowners to select the most sustainable hull maintenance strategies.

A demonstration case with different scenarios was included to illustrate how HullMASTER can be used and how to interpret its results. All scenarios were using a median-powered general cargo vessel in combination with two routes in the Baltic Sea region, Gothenburg-Kiel (route A) and Karlshamn – Klaipeda (route B). For each route, economic and societal cost-differences were calculated based on three scenarios; business as usual (BAU) where the vessel is assumed to be coated with a copper-coating, and two alternative scenarios where the vessel is

using either a biocide-free foul-release coating or an inert biocide-free coating with in-water hull cleaning. The results showed statistically significant socio-environmental cost savings in order of ~250k €/year in one of the routes (Route A, Gothenburg-Kiel) when the foul-release scenario was compared to the biocidal copper coating scenario. The socio-environmental cost differences were mainly governed by the high release of copper and zinc from the copper-based coating and the associated impacts on marine ecosystems. The operator cost (bunker and maintenance) is similar, for the foul-release coating compared to the copper-based coating, irrespectively of route. Thus, switching from traditional copper-based coatings to FRCs is favorable for the environment without leading to any increased costs for the operator.

HullMASTER is currently developed and validated for the Baltic Sea region, but the geographical scope could be extended in future developments of the tool towards worldwide shipping operations. Shipowners and charterers would benefit from a non-commercial, evidence-based decision support tool on the sustainability of hull surface maintenance strategies. Moreover, HullMASTER's is also important and highly useful for environmental and transport authorities who need to weigh impacts of measures or policies on vessels operating under their jurisdiction.



Sammanfattning

Internationell sjöfart spelar en viktig roll i världens transportsystem och ger socioekonomiska fördelar för samhället. Sjöfarten är dock också en verksamhet som står för en rad olika utsläpp, t.ex. växthusgaser, luftföroreningar och kemikalier, vilket påverkar luftkvaliteten, människors hälsa och den marina miljön. En särskild utmaning för sjöfart är att skroven koloniseras av marina arter och denna påväxt påverkar fartygets energieffektivitet, vilket i förlängningen leder till ökad bränsleförbrukning, luftutsläpp och kostnader för fartygsägaren. Det vanligaste sätter att förhindra påväxt är att måla skrovet med giftiga biocidinnehållande båtbottenfärger, s k antifoulingfärger, vilket dock kan medföra negativa konsekvenser för den marina miljön.

Att beräkna utsläppen från ett givet fartyg är mycket komplicerat då dessa är kopplade till bl.a. vilken typ av antifoulingfärg och underhållsstrategi som fartyget använder, typ av motor, bränsleval och eventuella avgasreduceringssystem. Utsläppen kommer också att vara beroende av fartygsrutten, eftersom intensiteten av skrovpåväxt varierar geografiskt (vilket påverkar luftutsläpp och bränsleförbrukning) medan biocidutsläpp från antifoulingfärgerna beror på salthalt och temperatur i det omgivande vattnet. Därav krävs i regel fartygsspecifika rekommendationer för skrovunderhåll som dessutom måste beakta vilken rutt fartyget har. I denna rapport presenterar vi ett fristående kostnadsberäkningsverktyg, HullMASTER (Hull Maintenance Strategies for Emission Reduction), speciellt utvecklat för att lösa denna komplicerade uppgift.

I HullMASTER har modeller utvecklats, vilka simulerar utsläpp till vatten och luft i olika scenarier för skrovunderhåll för fartyg med rutter i Östersjöregionen. En regionspecifik modell för påväxttillväxt, baserad på fältdata från Östersjön, har implementerats för att prediktera vilken ökad energiförbrukning olika typer av påväxt medför för fartyg. Modellen och dess simuleringar har validerats med ombordmätningar av energiförbrukning från nio fartyg (motsvarande 40 års drift) som verkar i Östersjöregionen. Resultaten visar på en mycket god överensstämmelse. Baserat på den predikterade energiförbrukningen som påväxten medför och en biocid-modell beräknar HullMASTER utsläpp till luft och vatten samt i förlängningen även skillnaderna i samhällsekonomiska externa kostnader p.g.a. effekter på mänsklig hälsa, klimat och vattenkvalitet mellan olika scenarier. Dessa presenteras tillsammans med de ekonomiska kostnaderna för fartygsredarna (d.v.s. underhållskostnader, ökade energiförbrukningskostnader på grund av påväxt och kostnader för eventuell skrovrengöring i vatten) för att redarna ska kunna välja de mest hållbara underhållsstrategierna för fartygsskrovet.

Projektet utförde även en fallstudie, med olika scenarier, för att illustrera HullMASTER och hur dess resultat kan användas. I scenarierna användes ett lastfartyg som färdades längs två olika rutter i Östersjöregionen, Göteborg-Kiel (rutt A) och Karlshamn – Klaipeda (rutt B). För varje rutt beräknades ekonomiska

kostnader för redaren samt samhällsekonomiska externa kostnader utifrån tre scenarier; business as usual (BAU) där fartyget antas vara målad med en giftig kopparfärg, och två alternativa scenarier där fartyget använder antingen en biocidfri silikonfärg eller en inert biocidfri färg (isbrytarfärg) i kombination med skrovrengöring. Resultaten visade statistiskt signifikanta kostnadsbesparingar avseende externa samhällskostnader i storleksordningen ~250 000 €/år på en av sträckorna (rutt A, Göteborg-Kiel) när biocidfria silikonfärger jämfördes med en kopparbaserad antifoulingfärg. De externa samhällskostnaderna berodde huvudsakligen av det höga utsläppet av koppar och zink från den kopparbaserade antifoulingfärgen och dess negativa effekt på marina ekosystem. Resultaten visade även att de ekonomiska kostnaderna för fartygsredaren (bunker och underhåll) inte skiljer sig åt mellan silikonfärgen och den kopparbaserade färgen. Slutsatsen från denna fallstudie är att biocidfria silikonfärger, till skillnad från kopparbaserade färger, är gynnsamt för miljön utan att påverka kostnaden för redaren

HullMASTER är för närvarande utvecklad och validerad för Östersjöregionen, men modellen har förutsättningen att utvecklas för ett europeiskt eller globalt användningsområde. Vidare är HullMASTER kostnadsfritt att använda för redare och andra intressenter och lämpar sig utmärkt som beslutsstöd och hållbarhetsklassning av olika antifoulingstrategier. Slutligen är HullMASTER även användbart för myndigheter för att analysera och beakta hur olika åtgärder och/eller regelverk påverkar utsläpp, miljöeffekter och kostnader.

Contents

1 Introduction

The use of effective antifouling strategies is essential for ship operators since the attachment of marine organisms (so-called biofouling) increases the frictional resistance which can be translated to increased fuel consumption, emissions of greenhouse gases, air pollutants, and increased maintenance costs. Through history, several effective techniques have been used to combat biofouling. It has been reported that tar, asphalt and copper sheathing was used on ship's hull already by the Phoenicians for more than 2000 years ago (Yebra et al., 2004). Antifouling paints started to be developed in the 1800s where toxic compounds such as copper oxide, arsenic, and mercury oxide were common ingredients (Yebra et al., 2004). Around 1950, organometallic paints (with e.g., tin, mercury and arsenic) were developed which in the early 1960s gave rise to tributyltin (TBT) based coatings. TBT was proven to be extremely effective and as a result 70–80% of the worlds fleet used TBT-paints in 2004 (Yebra et al., 2004). However, TBT was also extremely toxic to other non-target organisms causing severe effects on marine ecosystems (Alzieu, 2000; Bettin et al., 1996) and as a result a global ban was issued in 2008 through the adaptation of the AFS-convention by the International Maritime Organization (IMO). Today, most coatings on the global market are based on copper oxide as it is a relative cheap biocide, effective towards a wide spectrum of organisms and easy to apply in a coating (Amara et al., 2018). However, many algal species are known to be tolerant to copper and hence to increase the efficacy many copper-based coating also contain so-called booster biocides designed to target photosynthetic organisms (Almond and Trombetta, 2017). The historical use of TBT-based coatings and the current widespread use of copper-based antifouling paints have caused severe impact on marine ecosystems. For example, in Swedish coastal water bodies, 86% of sediment samples show concentrations of TBT exceeding the threshold value defining good environmental status (GES) according to the Water Framework Directive (Lagerström and Ytreberg, 2018). For copper, 76% of all sediment data points in the Baltic Sea exceed the threshold value defining GES (Lagerström et al., 2021a). Thus, it is important to reduce the input of both TBT and copper to the Baltic Sea in order to improve the environmental status of the Baltic Sea.

The total annual load of copper (Cu) to the Baltic Sea from various sources has recently been compiled by Ytreberg et al. (2021b) (**Figure 1**). In total, the Baltic Sea is receiving 1560 tonnes Cu annually, of which riverine input contributed to 54 % of the total input (850 tonnes) while maritime shipping and leisure boating together accounted for 37 % of the load (575 tonnes). Thus, more than a third of the total load of copper can be reduced if copper-free antifouling paints or other biocide-free antifouling strategies are used on ships and leisure boats.

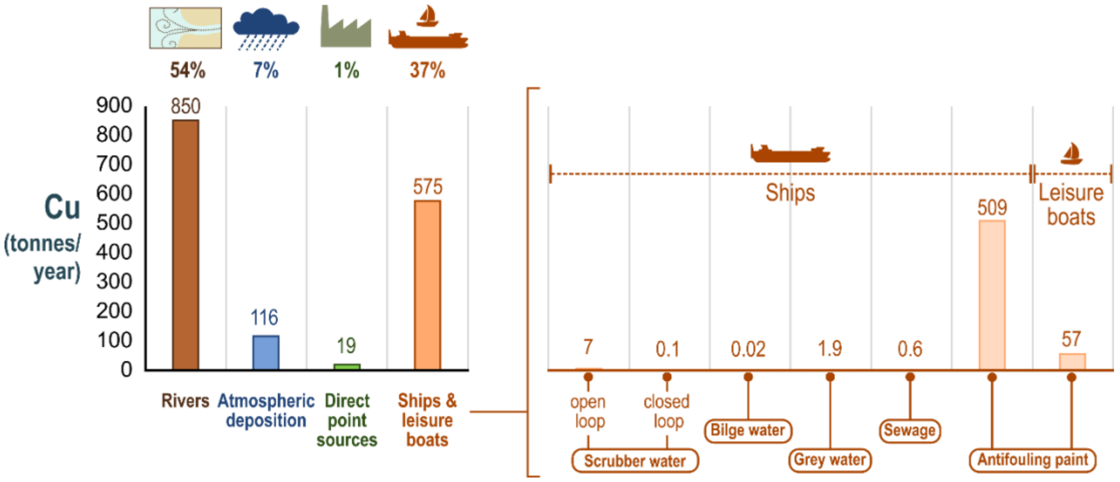


Figure 1. Comparison of loads (tonnes/ year) of Cu (A), Zn (B) and V (C) from rivers, atmospheric deposition, direct point sources, and direct discharges from ships and leisure boats to the Baltic Sea. Modified from Ytreberg et al. (2021b).

Alternatives to copper-based antifouling paints exist including biocide-free silicone foul-release coatings (FRC) and inert coatings combined with in-water hull cleanings. However, neither foul-release coatings nor copper-based antifouling coatings are suitable for ice-going vessels since the ice will damage and/or remove the paint. Therefore, inert coatings are more appropriate to be used on ships sailing in the northern part of the Baltic Sea during wintertime.

In order for shipowners to select the most sustainable hull maintenance strategies, there is a need to compile and communicate available data on economic performance together with environmental and societal impact of different antifouling technologies. Previous studies have focused on economic and environmental trade-offs of in-water hull cleaning (Pagoropoulos et al., 2018), 2018), and life cycle comparison of biocidal versus non-biocidal coatings (Demirel et al., 2018). Combined with models for fouling growth (Uzun et al., 2019b), it has been possible to calculate CO_2 emissions from both operation and hull maintenance (Uzun et al., 2019a). However, no study has yet provided estimates on emission uncertainties in order to statistically compare different hull maintenance scenarios. Also, in light of a recent valuation framework on societal costs of ship emissions (Ytreberg et al., 2021a), a decision-support tool that compiles existing and new data on environmental impact and economic performance of hull maintenance strategies is called for.

1.1 Aims and structure of the report

The overall aim of this project was to describe, validate and demonstrate a Life Cycle Cost analysis (LCC) tool developed to determine the most sustainable hull maintenance strategy for a given ship. The LCC tool, HullMASTER – Hull MAintenance STrategies for Emission Reduction, allows stakeholders, including shipowners, charterers, and authorities, to compare hull maintenance strategies in terms of costs for operators, as well as to costs of environmental and human health degradation. Thus, HullMASTER enables stakeholders to weigh externalities (societal costs) against economics of hull maintenance. The scope of HullMASTER is limited to vessels operating in the Baltic Sea region, even though the framework is more widely applicable.

HullMASTER is based on a large data set developed both within the project and extracted from other studies through extensive literature reviews. Data and input from stakeholders (e.g., shipping companies, shipyards, paint companies, hull cleaning companies, etc.) was also crucial for the development and validation of the tool (**Figure 2**).

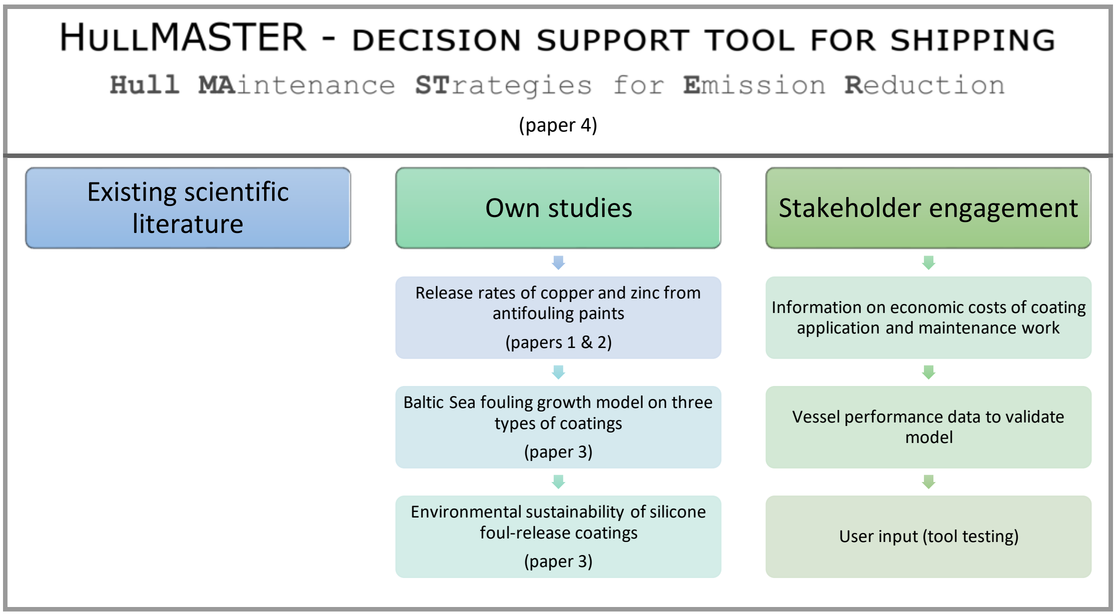


Figure 2. The three sources of information used to fill knowledge gaps and acquire necessary input for the LCC tool HullMASTER. For the list of papers (e.g., scientific articles), see **Table 1**.

Our own studies were conducted to fill knowledge gaps identified early in the project. HullMASTER models emissions and costs for three types of hull coatings:

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

After reviewing the scientific literature, the following knowledge gaps for these three coating types were identified and needed to be filled to develop HullMASTER:

i. measurements of copper release rates from commercial antifouling paints exposed in different Baltic Sea basins

ii. predicting the growth of biofouling on all three coating types in the Baltic Sea region
iii. assess if the use of biocide-free silicone foul-release coatings may pose a risk for adverse effects on the marine environment

To fill these knowledge gaps, the project firstly focused on developing an analytical application, based on X-Ray Fluorescence (XRF), to quantity copper in antifouling paints (paper 1). Secondly, the project used the XRF-methodology to determine release rates of copper from several commercial paints (paper 2). The data was later included in the HullMASTER but also used to determine the critical release rate of copper in different Baltic Sea regions (defined as the minimum release rate needed to prevent macroscopic biofouling). Thirdly, the project assessed how effective different antifouling coating categories are in preventing biofouling when exposed in Swedish coastal waters for up to 12 months (paper 3). And finally, a literature review was conducted to assess if silicone foul-release coatings are a viable and sustainable alternative to biocidal antifouling coatings in the Baltic Sea region (paper 3). The findings from these four tasks are presented briefly in this report (section 2.1–2.4), while a more extensive analysis is given in the related scientific articles (**Table 1**).

The subsequent sections in this report (3.1–3.3) present the development and demonstration of HullMASTER with respect to the specific aims of this report which were to:

- Develop a LCC tool to determine the most sustainable hull maintenance strategy for a given ship (section 3.1)
- Stakeholder engagement and validation of HullMASTER (section 3.2)
- Analyse if retrofitting from a conventional biocidal antifouling coating to a non-biocidal coating would provide economic and/or societal savings (section 3.3)
- Describe knowledge gaps and future development of HullMASTER (section 3.4)

A more comprehensive description about HullMASTER is given in the submitted scientific manuscript (paper 4, **Table 1**); and the tool itself and the manual can be downloaded here (https://research.chalmers.se/publication/527711).

Table 1. Scientific papers that have resulted from the HÅLL project and are described in this report.

Paper	Title	Status
1	Lagerström, M., & Ytreberg, E. (2021). Quantification of Cu and Zn in antifouling paint films by XRF. Talanta, 223, 121820. https://doi.org/10.1016/j.talanta.2020.121820	Published
2	Lagerström, M., Ytreberg, E., Wiklund, A.-K. E., & Granhag, L. (2020). Antifouling paints leach copper in excess – study of metal release rates and efficacy along a salinity gradient. Water Research, 186, 116383. https://doi.org/10.1016/j.watres.2020.116383	Published
3	Lagerström, M., Wrange, A.-L., Oliveira, D. R., Granhag, L., Larsson, A., & Ytreberg, E. (2021). Are silicone foul-release coatings a viable and sustainable alternative to biocidal antifouling coatings in the Baltic Sea region? Preprint (Version 1) available at Research Gate DOI: http://dx.doi.org/10.13140/RG.2.2.27758.54080/1	Submitted and under review
4	Oliveira, D.S.R. de, Lagerström, M., Granhag, L., Werner, S., Larsson, A.I., Ytreberg, E., 2022. A novel tool for cost and emission reduction related to ship underwater hull maintenance. Link to pre-print (https://research.chalmers.se/publication/?created=true&id=ff897d03-41e2-48cc-a789-163dcfc260d5).	Submitted and under review

2 Identified knowledge gaps and how they were solved

2.1 Method development to measure copper in antifouling paint

Determination of release rates of copper (Cu) and zinc (Zn) from antifouling paints at different salinities was required in order to model metal emissions from a ship's coating for the copper paint scenario in HullMASTER. Previous studies have shown that salinity can impact the release of copper significantly. An increase in salinity from 5 to 14 ‰, for instance, has shown to double or even triple the emissions of copper, depending on the paint (Lagerström et al., 2018). A method utilising X-Ray Fluorescence (XRF) analysis to determine metal release rates from antifouling paints exposed in the field was originally developed by Ytreberg et al. (2017). The method is based on a simple principle with the following steps (**Figure 3**):

1. Panels are coated with antifouling paint
2. The area concentration (in µg/cm^2) of the metal is determined by XRF through measurement on pre-determined analysis spots
3. The panels are exposed in the field for a given time
4. The panels are retrieved, left to dry, and measured again by XRF in the same analysis spots

The release rate (in µg per cm^2 of paint and day, µg/cm^2/d) is then determined as the difference in concentration between the two time points (i.e., the metal loss that has occurred, in µg/cm^2) divided by the exposure time (in days).

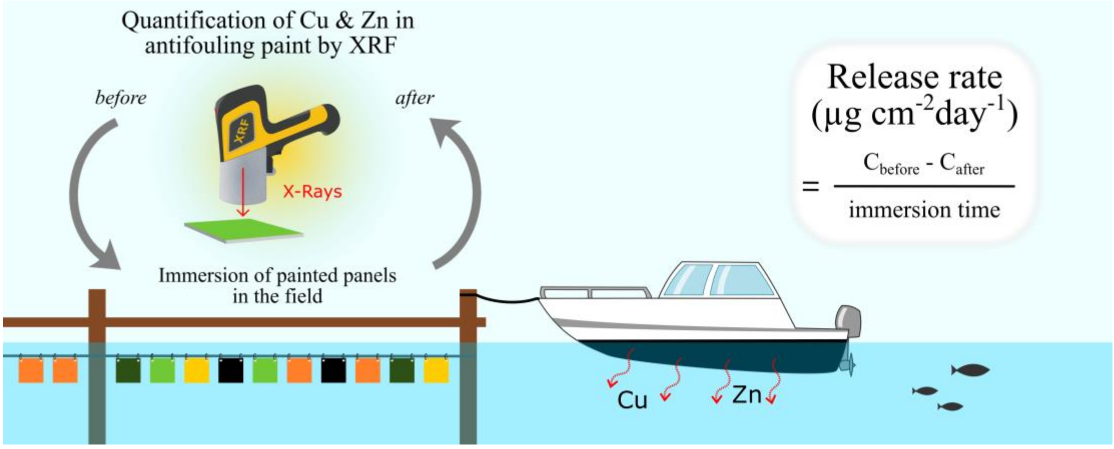


Figure 3. Schematic showing the principle behind the XRF release rate method.

The XRF release rate method required however some further assessments and refinements. In particular, the effect of paint formulation on the accuracy of the method needed to be investigated and a calibration with a wider range in concentrations was also required. For the former, variations in Cu and Zn concentrations between products, as well as that of other elements present in fillers/extenders (e.g., barium sulphate, calcium carbonate, etc) or colour pigments (e.g., iron oxide, titanium oxide, etc) was found to not affect the measurement. For the latter, i.e., the extended calibration, new standards were developed by mounting small pieces of antifouling paint films in plastic XRF cups (**Figure 4**). This design allows for an interchangeable background panel, i.e., the panel placed behind the standard film can be made to exactly match the panel type used in a field experiment. Further details about the developed method can be found in paper 1 (**Table 1**). The new standards were used to establish a calibration enabling the measurement of copper and zinc release rates from eight different coatings exposed to four different salinities, as described next in section 2.2.

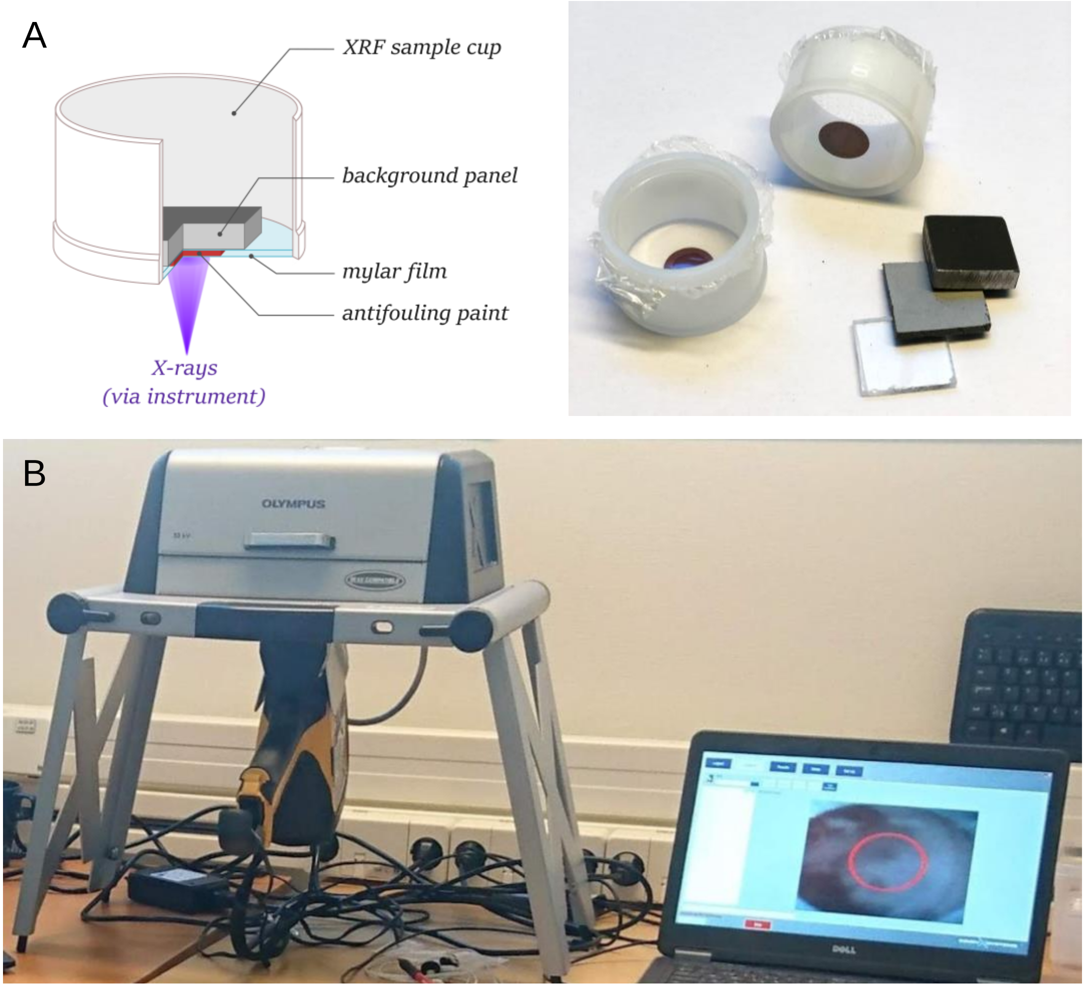


Figure 4. New XRF standards (A) shown both as a schematic and in a photo with example different types of background panels (plastic and metal) and analysis of the standards to establish a new calibration curve (B) by XRF. Here, the XRF is mounted upside down onto a benchtop stand into which standards (and later samples) were placed for analysis. A camera inside the instrument enables visualization of the analysed standard or sample.

2.2 Release rates of copper in different Baltic Sea basins

In paper 2, the release rates of copper from eight commercial paints at four different salinities were determined by XRF (**Figure 5**). In addition, the efficacy of the coatings to prevent biofouling was assessed after 5 months exposure. The studied coatings held different amounts of copper, ranging from 6 to 33 wt% cuprous oxide. The coatings were either of hard (coatings H1-H4) or polishing (P1-P4) type in order to investigate whether the effect of coating type on both the release rate and the efficacy. The coatings were applied on panels and exposed at four different sites: Lake Mälaren (0 ‰), Baltic Proper (6.4 ‰), Öresund (7.5 ‰) and Kattegat (27 ‰).

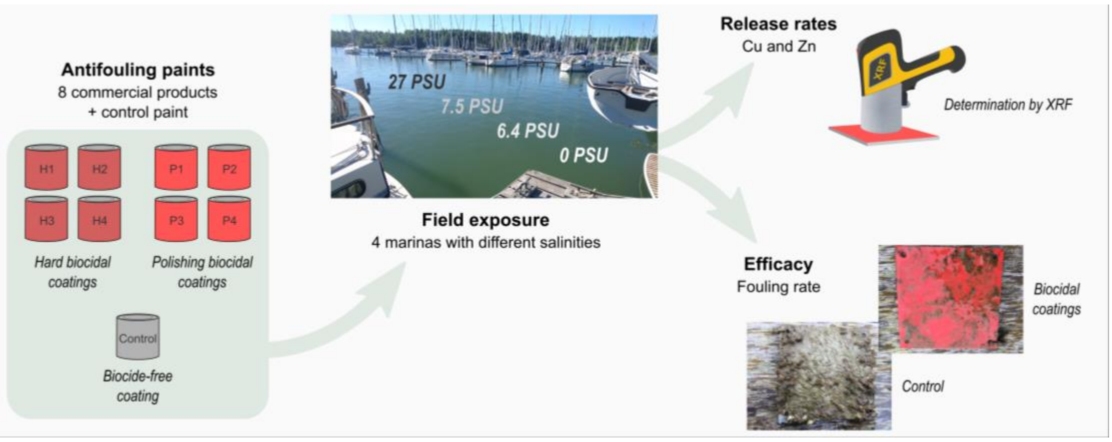


Figure 5. Study design to evaluate the effect of salinity on 8 different coating types and to assess their efficacy.

The results showed salinity to be a critical parameter governing the release rate of copper for all the studied coating, with a linear increase in release rate with increasing salinity. To correctly model the emissions and environmental impacts of using copper-based antifouling paints, it is thus important to take salinity into consideration. No significant effect of salinity was however detected on the release rate of zinc. These findings were implemented into HullMASTER. Copper coatings for ships are most commonly of polishing type and coating P4 contains a cuprous oxide concentration similar to most paints that are available on the Swedish market for commercial ships. The release rate from coating P4 was therefore later used in the HullMASTER to describe emissions of copper and zinc from a typical copper-based antifouling paint, which included adjustments of the copper release rate depending on the salinity of the specified route.

The efficacy evaluation of the coatings in this study also showed all eight coatings to be efficient in preventing fouling despite large variations in their release rates of copper. This indicates that several of the tested coatings were leaching unnecessarily high amounts of copper. On a global scale, over 1,000 unique antifouling paints are registered on the market (Paz-Villarraga et al., 2022). Most coatings (76%) contain copper (as cuprous oxide) but the concentration added to the paint formulation varies substantially from 3.7 to 76%, by wet weight. From an environmental perspective, it is important that the coatings do not leach more copper than what is necessary to prevent biofouling. The critical release rate (RR_{crit}) describes the leaching rate of an active substance, such as copper, needed to prevent the attachment of a given fouling organism or group of organisms (WHOI, 1952). If macrofouling, defined as multicellular organisms visible to the human eye, are considered as a whole, the critical release rate refers the lowest release rate (in µg/cm^2/day) resulting in 0% surface coverage of macrofouling on a coating. This threshold will however vary between sea areas and depends on the prevailing fouling pressure, i.e., the intensity and type of fouling organisms in the specific region. Results from this and previous studies on copper release rates in the Baltic Sea has enabled the mapping of the critical copper release in different parts of the Baltic Sea region (**Figure 6**). The map reveals variations in the sensitivity of the fouling community in the Baltic Sea/Kattegat area, with higher release rates required to deter macrofouling at higher salinities.

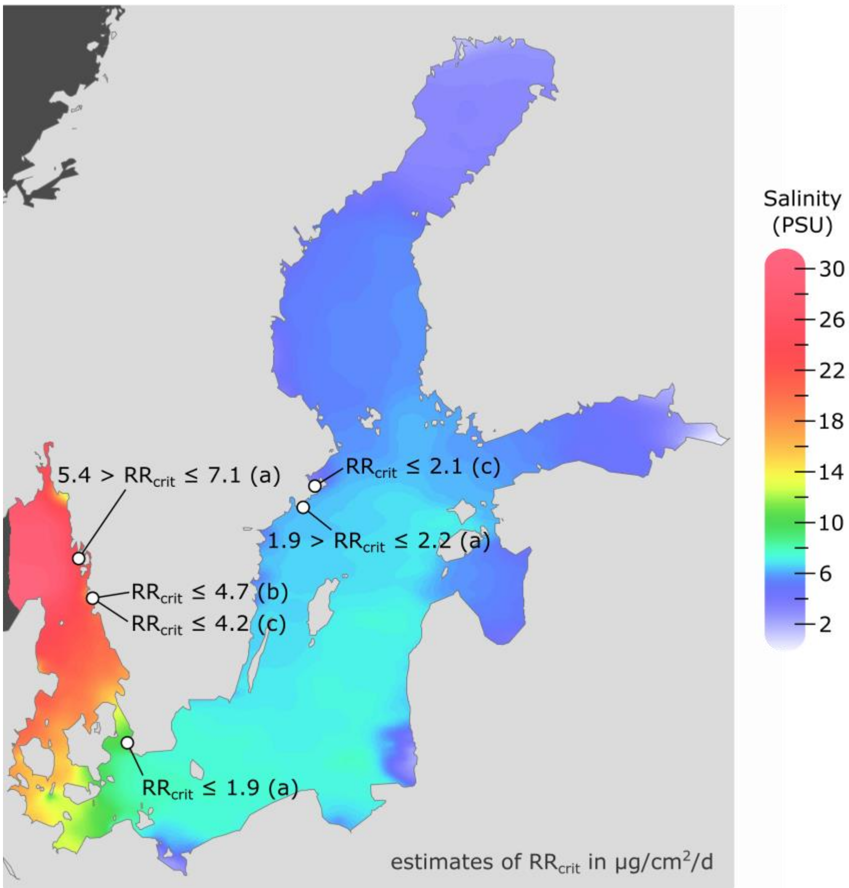


Figure 6. Salinity map of the Baltic Sea showing estimates of the critical copper release rates (RR_{crit}) at five locations along the Swedish coast from Lagerström et al., 2020 (a), Lindgren et al., 2018 (b) and Lagerström et al., 2018 (c). For more details on how the critical release rates in this map were determined, see paper 2 (**Table 1**).

Coating P4, used to model emissions in HullMASTER, leached 8, 12 and 28 μg/cm²/day in the Baltic Proper, Öresund and Kattegat, respectively. This can be compared to the RR_{crit} which are 2, 2 and 5 μg/cm²/day in the Baltic Proper, Öresund and Kattegat, respectively (**Figure 6**). Hence, coating P4 emitted between 4 to 6 times more copper to the marine environment than what was necessary to prevent macrofouling. Thus, an easy measure for shipowners to reduce their environmental footprint would be to shift to a low-leaching copper paint. However, these low-leaching copper paints are typically only available for the leisure boat sector, which makes it difficult for shipowners to make sustainable choices regarding antifouling practices.

Apart from their utilisation in HullMASTER, the results from this particular study have also been communicated to various national and international authorities as the findings have been presented to both the Swedish Chemicals Agency (KemI) and the European Chemicals Agency (ECHA) and highlighted in a report commissioned by the European Commission (European Commission, 2021).

2.3 Efficacy and sustainability of different hull coatings in the Baltic Sea region

A model to predict the amount of fouling that grows on a given hull was needed in HullMASTER order to estimate the resulting powering penalty due to increased hull roughness. Hence, a fouling growth model specific to the Baltic Sea region was needed for each of the three considered coatings in HullMASTER. Additionally, the sustainability of silicone-foul release coatings with respect to marine ecotoxicity was needed for their cost evaluation. Both knowledge gaps were addressed in the work conducted in paper 3 (**Table 1**).

Today, the most common strategy to prevent the attachment of fouling organisms is to coat a vessel's hull with biocidal antifouling paints (Amara et al., 2018). Many of these products have shown to be efficient for several years but it is not a sustainable practice since the paints also leach toxic compounds affecting non-target species and marine ecosystems. The use of copper leaching products is of particular concern for the Baltic Sea region as it is a heavily trafficked marine region by ships and recreational boats. It has been estimated that at least 2,000 ships navigate within its borders at any given moment, and shipping is projected to increase as a result of the modal shift of transport from road to sea that is desired in Europe (Matzcak et al., 2018). The leading market alternative to traditional biocidal coatings are so called foul-release coatings (FRCs), which act to prevent the attachment of fouling organisms through physical, rather than chemical, action. They prevent the attachment of biofouling by means of their non-stick properties. The slippery nature of their surface act to reduce the adhesion strength of fouling organisms which can then be readily removed by the water shear force during cleaning or navigation, the latter enabling the coating to "self-clean" (Townsin and Anderson, 2009). These coatings can have either silicone- or fluoropolymer based binders, but all commercially available systems are silicone-based (Lejars et al., 2012). Today, all major coating companies with paint products for marine application, market at least one silicone-based product (Kim, 2021). Whereas silicone FRCs held less than 1% of the ship market in 2009, this share had risen to nearly 10% in 2014 (Ciriminna et al., 2015).

However, little is known about how efficient these silicone FRCs are in preventing biofouling in the Baltic Sea region in comparison to traditional copper coatings. In addition, no recent review has been performed on if and how silicone FRCs may cause adverse environmental effects. These coatings are typically biocide-free, and thus generally considered environmentally friendly. Reviews on the ecotoxicology and environmental sustainability of silicone FRCs are however lacking in the current scientific literature. Finally, even though silicone coatings have been available commercially for over two decades, they hold a relatively small market share compared to traditional copper coatings.

In this study, we therefore attempted a holistic assessment of silicone FRCs to determine their applicability to vessels in the Baltic Sea Region (**Error! Reference source not found.**). The aim was to answer three main questions, put simply:

(1) How do silicone FRCs perform in the Baltic Sea in comparison to copper coatings and a biocide-free control paint?
(2) Are they truly environmentally friendly?
(3) Why aren't more ship and boat owners using them?

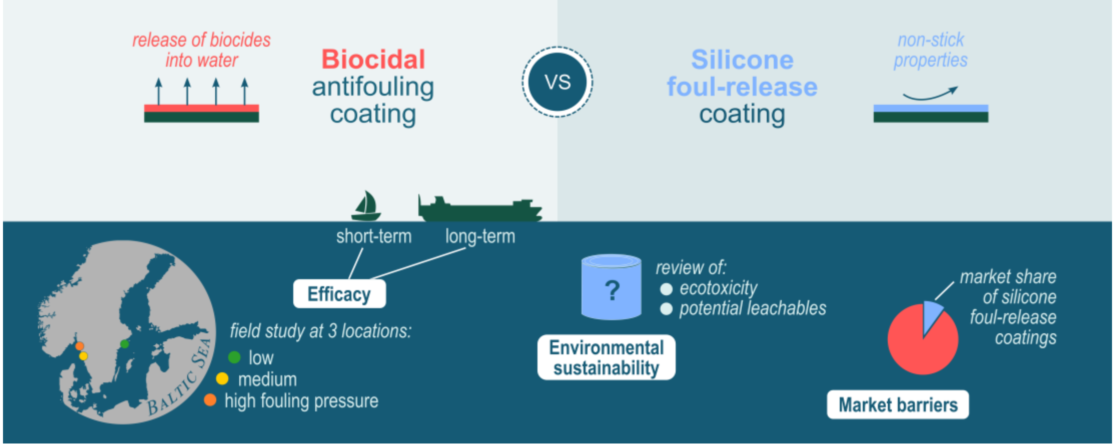


Figure 7. Design of the study including field efficacy experiments using a silicone foul-release coating and traditional copper-based coatings, environmental sustainability assessment of silicone foul-release coating and an analysis of market barriers.

We firstly assessed the efficacy of a silicone FRC in comparison to two copper coatings and a biocide-free control coating through a field study (question 1). Painted panels were exposed statically in the field at three locations in the Baltic

Sea Region holding low, medium, and high fouling pressures (**Error! Reference source not found.**). The performances of the coatings were then compared over a one-year period. Photographs of the coated panels, taken on roughly a monthly basis, were used to determine the type and extent of fouling on the painted surface. These observations were then converted into a weighted fouling rate (FR_w) which could be used to statistically compare the overall performance of the coatings. The fouling pressure to which the antifouling coatings were subjected during this study is illustrated by the photographs of the control coating (**Figure 9**). As exemplified by the photos in **Figure 9**, both the silicone and copper coatings were efficient in deterring fouling in comparison to the control coating at all study sites, including the one with the highest fouling pressure (Station 3).

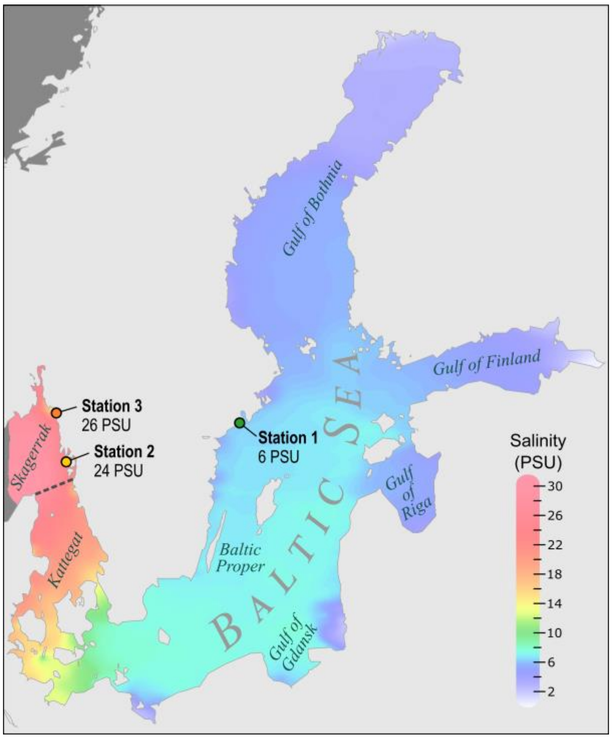


Figure 8. Map showing the location of the three stations (a). The average salinity during the study is indicated below each station.

The performance of the silicone FRC to the two copper-based coatings was evaluated through comparison of the calculated FR_w. The silicone coating was found to perform equally well or significantly better than the two copper-based coatings at all exposure sites (**Figure 10**). Similar results have been observed in the Gothenburg area where Oliveira and Granhag (2020) showed a silicone FRC to be more effective than a copper-based coating in preventing biofouling when coated panels were exposed statically for 12 months in Saltholmen, Gothenburg (Kattegat). This is particularly interesting given that the static exposure represents a worst-case scenario for the FRC in particular as removal of fouling on this coating by the water shear force would have taken place on a navigating ship. Likely, the performance of the FRC compared to the traditional copper ones would have been even more superior if the test had involved more dynamic conditions.

The recorded fouling ratings on the silicone FRC, the two copper-based coatings and the biocide-free control coating was later used to develop a salinity-dependent fouling growth model for the Baltic Sea region. The fouling model was subsequently incorporated in HuLLMASTER (see chapter 3.1.)

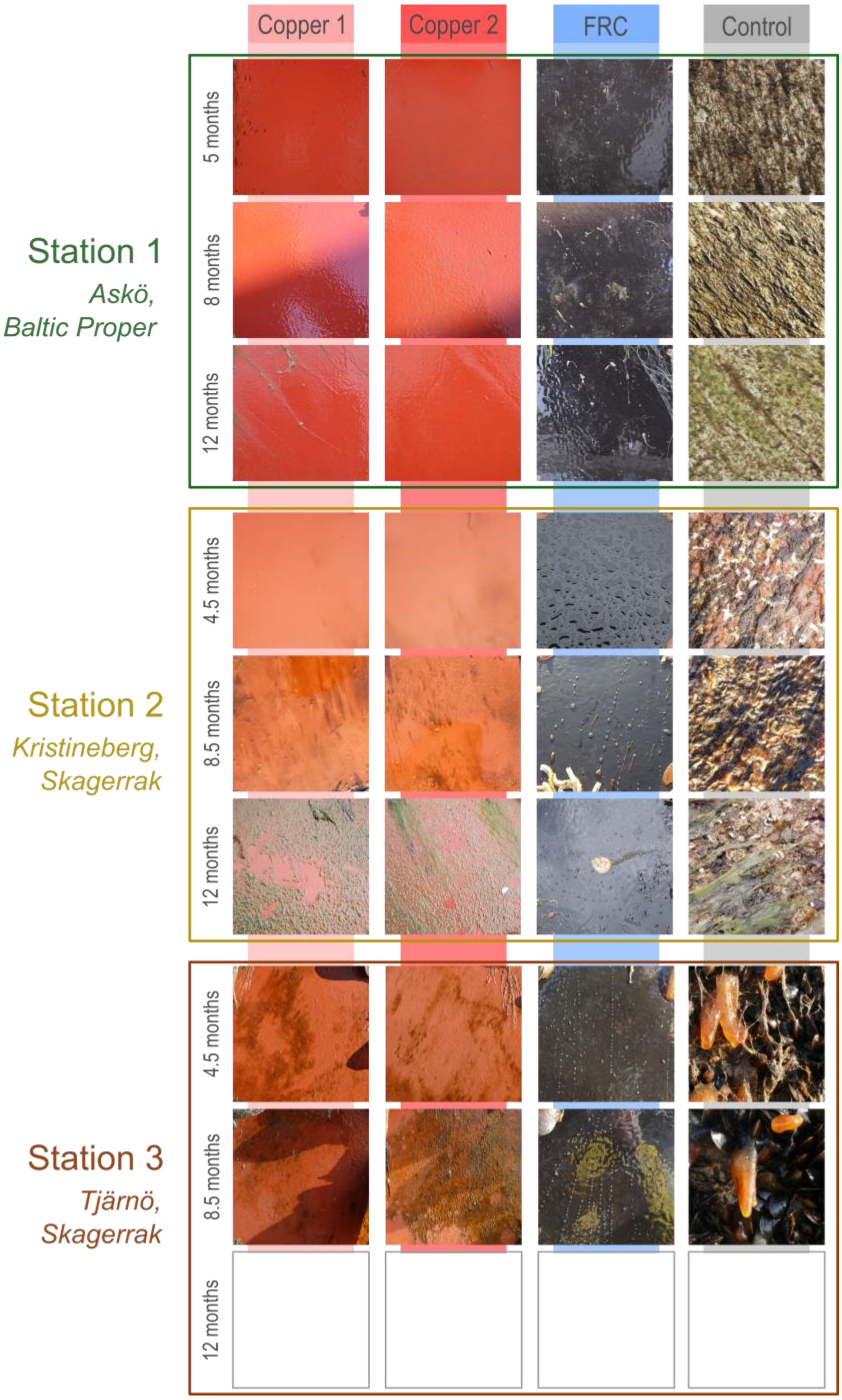


Figure 9. Example photographs of the coated panels and the control from three different time points Note that fouling growing within 13 mm of panel edges were not considered in the fouling rate assessment (for more details on the efficacy assessment, see paper 3, **Table 1**). The exposure at Station 3 was terminated ahead of time, after roughly 8,5 months due to disturbance of the panels by grazing eider ducks, likely feeding on the mussels growing on the control panels.

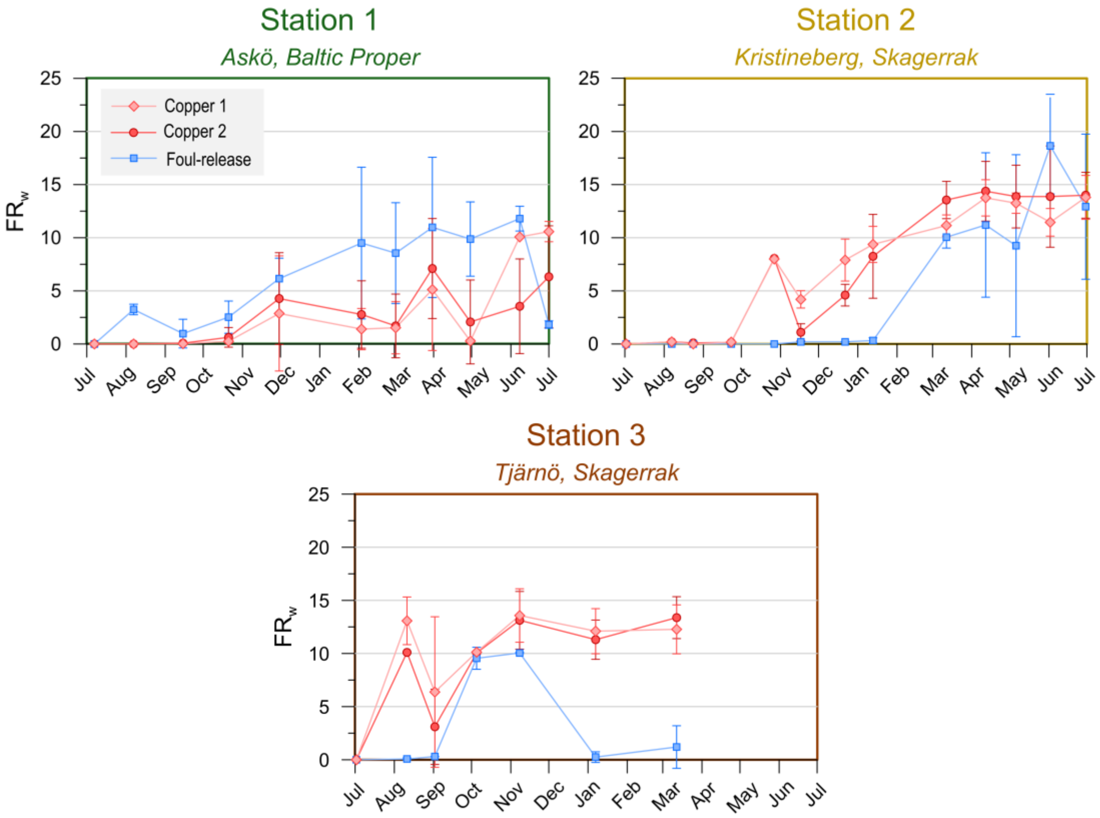


Figure 10. Calculated weighted fouling rate (FR$_w$) for the copper and silicone foul-release coatings at Station 1, 2 and 3. Error bars show the standard deviation (n = 4 panels).

As for the toxicity and environmental sustainability of commercially available biocide-free silicone coatings (question 2), a literature review was carried out in the second part of the study. In total, seven scientific studies, holding ecotoxicity data on 14 species exposed to commercial silicone FRCs, were identified, and used to assess environmental impact. Some studies did not identify any adverse effects, whereas others showed that some commercial products displayed toxicity to marine organisms, especially during the first months of immersion. The identity of the substance(s) responsible for the observed effects is however unknown. Except for a few products, most silicone FRCs on the market are biocide-free. As such, they are subject to less legal scrutiny compared to biocidal coatings. The sustainability of these coatings therefore essentially relies on producer responsibility. In reviewing the chemical composition of silicone FRCs, we found that there is a large variability in the formulation of commercial silicone FRCs and that they may not all be completely environmentally benign, simply for their lack of biocides. Several potential leachables from different commercial products which may be toxic and/or environmentally persistent were identified. These leachables included hydrophobic and amphiphilic silicone fluids, PFAS and organotin compounds. Efforts to limit or avoid their release should therefore be made by producers. Ultimately, more transparent studies investigating the potential toxic effects of commercial products as well as the identity of leachables and their environmental fate are needed. Nonetheless, the reviewed studies showed biocide-free silicone FRCs to have a substantially lower toxicity on marine organisms in comparison to biocidal copper coatings. Therefore, the socio-environmental costs related to impact on marine ecotoxicity was set to zero in HullMASTER. Given their lower toxicity, the use of FRCs should be promoted over that of conventional antifouling paints, which bring us to the final question.

In our assessment of market barriers (question 3), end-user scepticism was found to be one of the main reasons why both ship and boat owners are hesitant to transition from a copper coating to a silicone foul-release coating. For shipowners in particular, it seems that demonstration of improved performance, i.e., reduced fuel consumption, rather than sustainability arguments tend to convince shipowners to make the transition to a silicone coating. Not only is the performance of this coating typically better over time, resulting in fuel savings, but the service lifetime is also longer as silicone coatings do not rely on polishing or depletion mechanisms, resulting in extended dry-docking intervals. Independent studies on the efficacy of FRCs, such as the one carried out here (paper 3), and the development of independent evidence-based decision support tool, such as HullMASTER (described next and in paper 4) are thus needed to promote the use of more sustainable antifouling coatings in the future.

3 Development and scenario analysis of HullMASTER

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

HullMASTER was developed to allow a comparison between different hull maintenance strategies in terms of costs for operators, as well as to external costs due to environmental and human health degradation. At each life phase of the coating on a hull, activities that would result in a direct cost for the operator or an emission to the environment (and socio-environmental costs) were identified (**Figure 11**). Most of the cost assumptions were obtained through stakeholder engagement (see chapter 3.3). Text in grey italic in **Figure 11** indicate current exclusions in terms of types of emission and costs in HullMASTER. For details on the full scope of the tool, see paper 4 (**Table 1**).

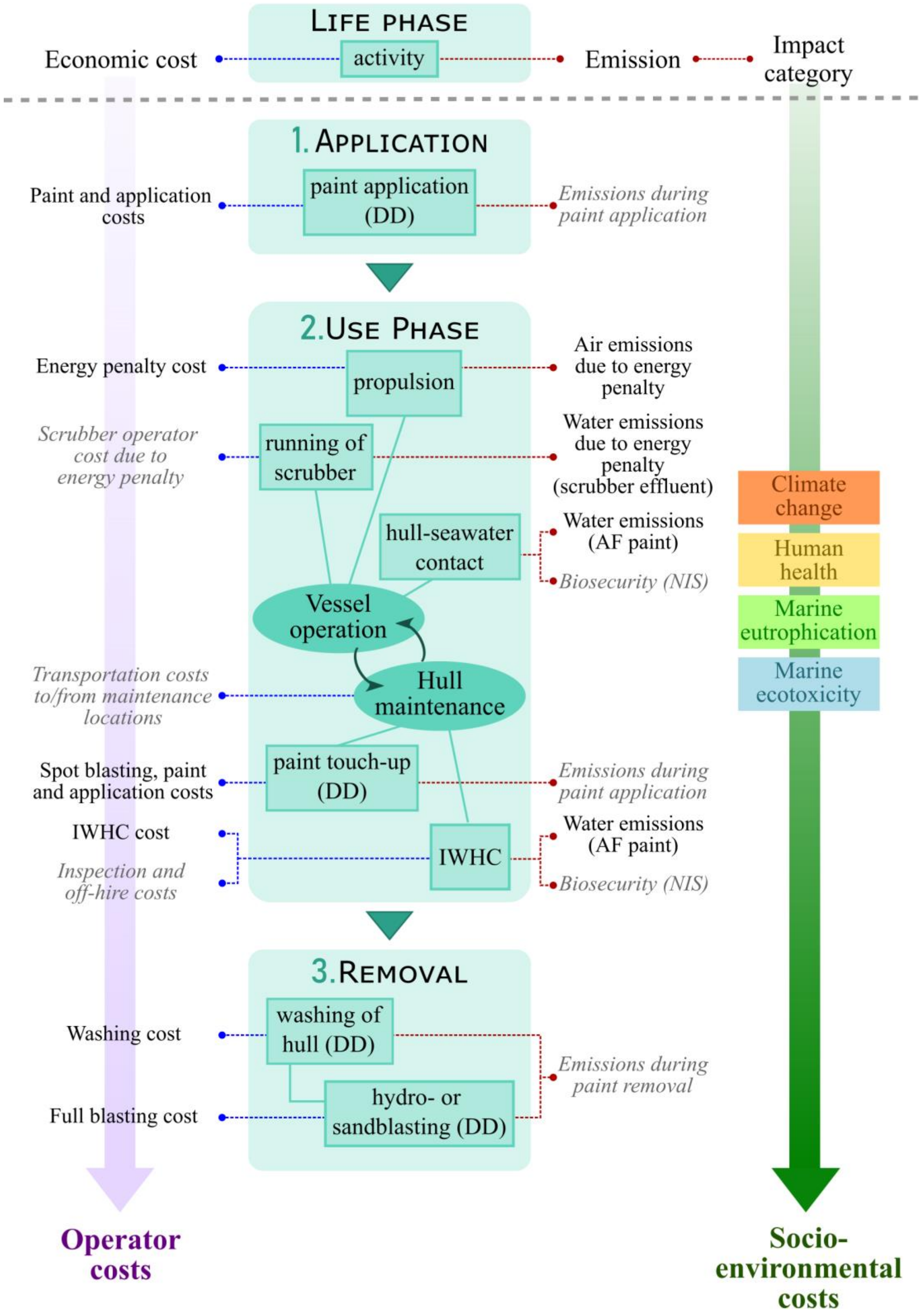


Figure 11. Economic costs and emissions considered in HullMASTER. Components excluded from analysis are given in grey italic text. Abbreviations: DD – dry docking; IWHC – in-water hull cleaning; AF – antifouling; NIS – non-native invasive species.

HullMASTER is implemented in Matlab® App Designer (version R2019b, MathWorks, Natick, MA, USA) and the tool is available as a standalone Windows application here (https://research.chalmers.se/publication/527711). HullMASTER features three specific components; input parameters, models, and calculations and finally a result section where costs are compared based on different scenarios (**Figure 12**). The input parameters include i) vessel specific parameters, e.g., vessel dimensions, engine type, energy carrier and fuel consumption ii) vessel activity and cruising speed iii) hull maintenance strategy, i.e., use of conventional copper coating, biocide-free FRC or inert biocide-free coating, dry docking interval and frequency, and in-water hull cleaning activity iv) pricing assumptions for hull maintenance, bunker cots, and societal and environmental external costs.

The user can either use pre-defined default values for all parameters or use their own ship-specific values. As almost all parameters can be edited by the user, this function allows a shipowner and/or charterer to compare hull maintenance strategies for a specific vessel in terms of costs for operators, as well as the associated external costs due to damage on human health and environment.

The second component, i.e., models and calculations, includes a fouling growth model for conventional copper coatings, biocide-free FRCs and inert biocide-free coatings. The fouling model which is based on Lagerström et al. (2021b) (paper 3, see chapter 2.3) and is used in the tool to predict hull-roughness propulsion penalties and associated emissions to the atmosphere and the marine environment. The models and calculation component also includes a biocide model, based on the data from Lagerström et al. (2020) (paper 2, see chapter 2.2), which calculates emissions of copper and zinc to the marine environment due to passive leching and during in-water hull cleaning.

The third and final component, the result section, include a cost comparison where different hull maintenances scenarios are compared to a business as usual (BAU) scenario, as defined by the user. The assessment includes differences in operator costs as well as socio-environmental costs due to ship emissions and impacts related to four impact categories: climate change, air quality (human health), marine ecotoxicity and marine eutrophication. The operator cost estimates were derived from stakeholder engagement from numerous sources including shipowners, paint manufacturer and shipyards, while the socio-environmental costs were obtained from Ytreberg et al. (2021a). Based on the review by Lagerström et al. (2021b) (paper 3, see chapter 2.3), only copper-based coatings are assumed to leach toxic compounds (copper and zinc) causing environmental costs due to impact on marine ecotoxicity, while no external costs for marine ecotoxicity is assumed for biocide-free silicon FRC or biocide-free inert coatings.

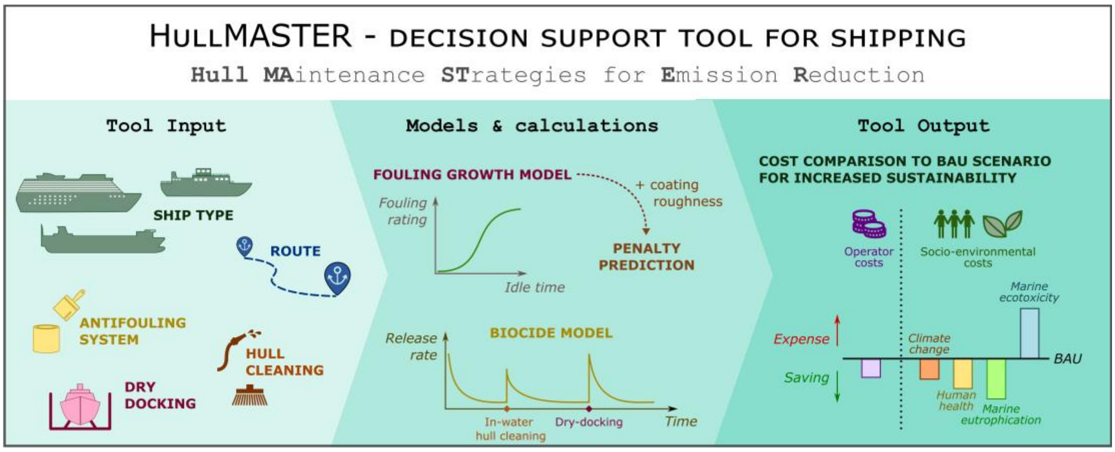


Figure 12. Overview of HullMASTER and the three main components; tool inputs, models and calculation and tool output.

3.2 Stakeholder engagements and validation of HullMASTER

Stakeholder engagement was vital in order to enable the development of, and validation of, HullMASTER. Shipyards and paint companies provided important knowledge on hull maintenance strategies for the different coatings (including the associated costs), i.e., hull surface preparations including washing and spot-/full-blasting of the hull, lifetime of the coatings and how frequent a vessel is repainted, thickness layer of the coating applied on the hull etc. Shipping companies provided costs for in-water hull cleaning and in-service performance data, represented as time series of propulsion powering penalty.

The accuracy of HullMASTER was assessed by comparing measured time series of propulsion powering penalty from nearly 40 vessel-years of in-service performance data from 9 vessels with predictions from HullMASTER. All vessels operate in the Baltic Sea region and had their hulls coated with either biocidal copper antifouling coatings, silicone FRCs or an inert abrasion-resistant biocide-free coating. Overall, HullMASTER predictions show good agreement with measured propulsion penalties across, with an average of difference between HullMASTER predictions and performance measurements of -3.2 ± 3.8 % (n = 9 vessels).

3.3 Demonstration of scenario-based approach in HullMASTER

In paper 4, a demonstration case with different scenarios was included to illustrate how HullMASTER can be used and how to interpret its results. All scenarios were using a median-powered general cargo vessel, as detailed in **Figure 13A**, in combination with two routes: Gothenburg – Kiel (Baltic Transition, Route A) and Karlshamn – Klaipeda (Baltic Proper, Route B). For each route, economic and societal cost-differences were calculated based on three scenarios; business as usual (BAU) where the vessel is assumed to be coated with a copper-coating (scenario 0), and two alternative scenarios where the vessel is using either a biocide-free foul-release coating (scenario 1) or an inert biocide-free coating with in-water hull cleaning (scenario 2) (**Figure 13A**). The results showed statistically significant socio-environmental cost savings in order of ~250k €/year in the Baltic Transition (Route A) when the foul-release coating scenario was compared to the biocidal copper coating scenario (**Figure 13B**). Minor cost differences were also observed for the inert coating (Scenario 2) as compared to the biocidal copper coating scenario, but uncertainties (see error bars) are larger than the cost differences. Marginal differences were also observed for all scenarios in Baltic Proper (route B), meaning that the overall societal cost of alternative coatings (foul-release and inert coatings) is not significantly lower than that of a conventional antifouling coating.

For both Routes A and B, the socio-environmental cost differences were mainly governed by the high release of copper and zinc from the copper-based coating and the associated impacts on marine ecosystems (**Figure 13B**, cost breakdown). The operator cost (bunker and maintenance) is lower, yet not significant, for the foul-release coating and would result in an average cost saving of ~20k €/year in the Baltic Transition (Route A) or ~15k €/year in the Baltic Proper (Route B), which are somewhat lower costs than the average bunker spending in a single week for the current vessel (~25k €). These marginal savings with a foul-release coating contrast with marginal cost increase for an inert coating, at ~37 to 47k €/year for each of the Baltic Proper and Transition operations (respectively), equivalent to the bunker spending of 1-2 weeks for this vessel.

Maintenance costs are almost identical among coatings (**Figure 13B**), despite initial higher investment for foul-release and inert coatings (30-50 €/m^2) compared to the copper-based coating (15-35 €/m^2), due to longer lifetime of the former, as well as somewhat lower touch-up maintenance costs (5-8 €/m^2 versus 3-12 €/m^2).

A. Input

Vessel specifics:

Vessel	Activity	Fuel & abatement techniques
General cargo vessel 132.2 m length, 10,000 DWT 3332 m^2 wetted surface area	Idle time: 40% (0.5 days idle, 0,8 days sailing) Average cruise speed: 12 knots	Ultra Low Sulphur Fuel Oil (0.07% Sulphur) No scrubber No NOx abatement

Maintenance scenarios:

Scenario	Hull coating	Dry docking scheme	In-water cleaning
0 (BAU)	Copper coating *(biocidal)*	0 – 2 – 4 years Coating application – Touch-up – Coating removal *assumed coating lifetime on the hull*	No
1	Foul-release coating *(biocide-free)*	0 – 2 – 4 – 6 – 8 – 10 years Coating application – Touch-up – Touch-up – Touch-up – Touch-up – Coating removal	No
2	Inert coating *(biocide-free)*	0 – 2 – 4 – 6 – 8 – 10 years Coating application – Touch-up – Touch-up – Touch-up – Touch-up – Coating removal	Yes Cleaning triggered at fouling rating > 40

B. Cost difference compared to baseline scenario

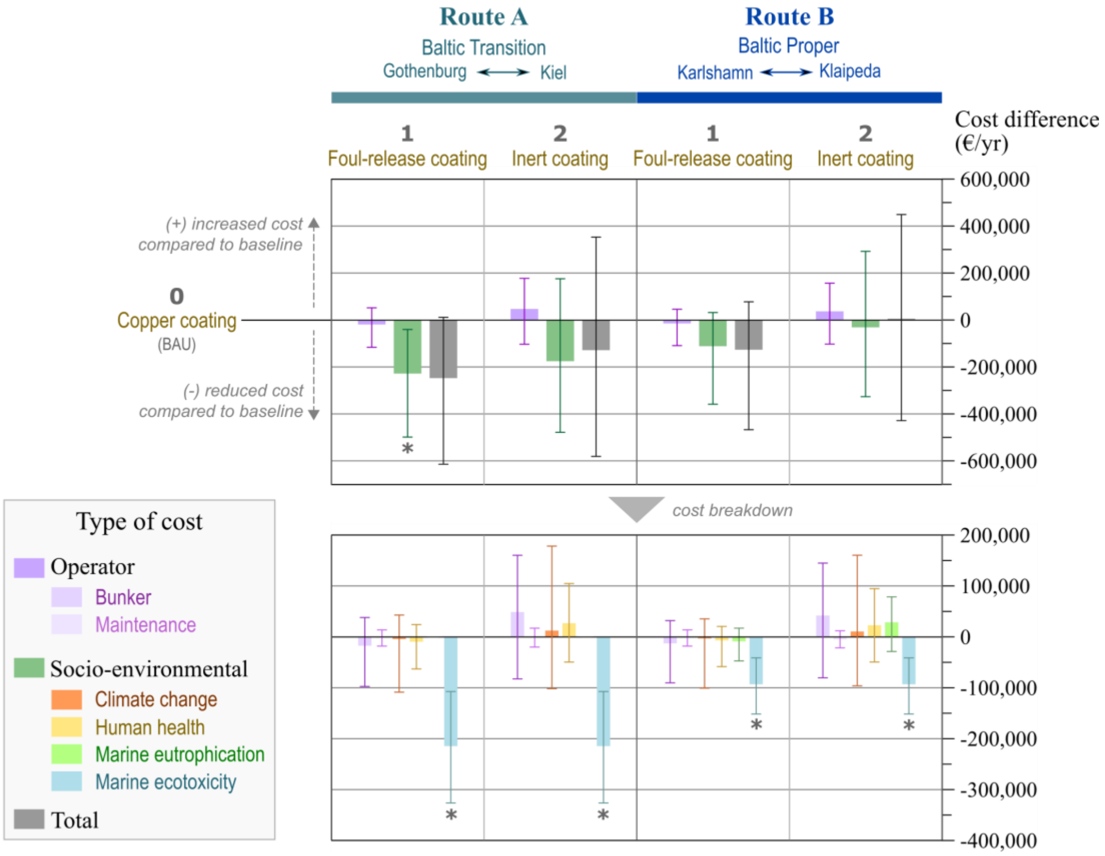


Figure 13. Demonstration example for HullMASTER: A – Input: main parameters; B – Output: cost difference. Asterixis show significant cost differences compared to BAU (Business-As-Usual).

3.4 Knowledge gaps and future development of HullMASTER

HullMASTER is currently developed and validated for the Baltic Sea region. The concept is however applicable globally, but it requires an updated fouling model and a biocide model for the tool to be able to expand to other sea areas. Regarding current assumptions and modelling, there are several aspects that require further data collection and research. Effects of in-water cleaning, vessel speed and navigation in other sea areas (including ice conditions) on fouling growth, coating performance and release of biocides need to be further investigated.

The current fouling model is based on performance data (fouling growth) on panels exposed statically for up to 12 months and does not take into account that fouling can be removed during vessel speed. Despite this conservative approach, the validation results showed good agreement between model predictions and in-service measured propulsion penalties.

A more complete compilation of knowledge gaps can be found in paper 4 (**Table 1**).

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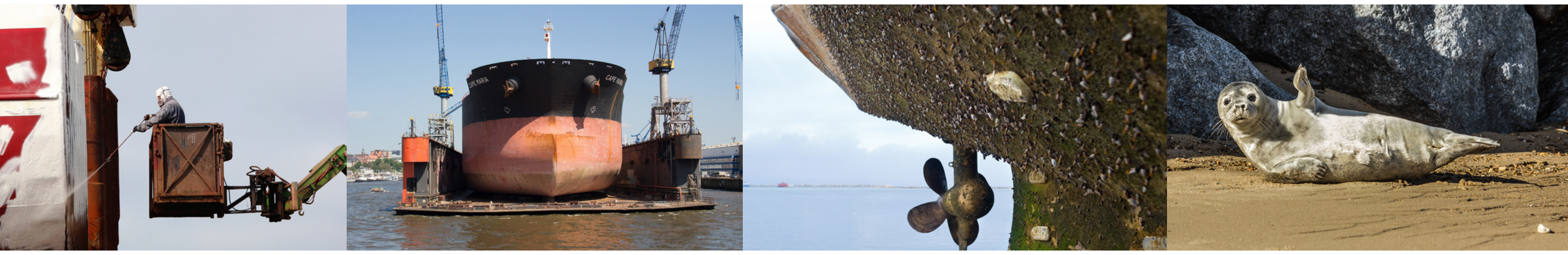

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