# A novel tool for cost and emission reduction related to ship underwater hull maintenance

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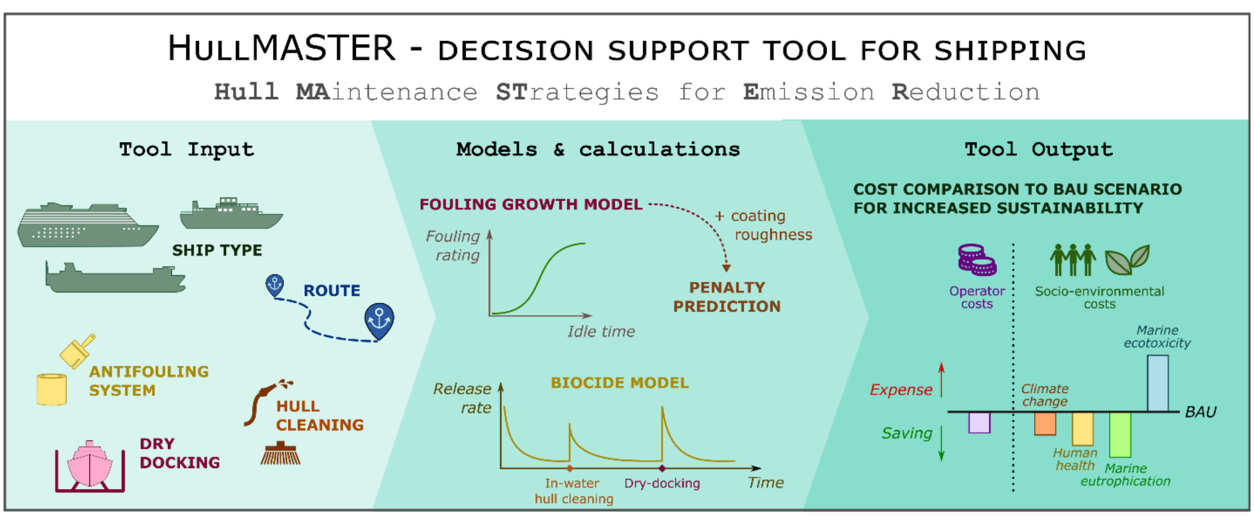
## Abstract

International shipping plays a vital role in the world's transport system and economy. However, shipping faces challenges in terms of reducing its environmental and health impact, namely emission of greenhouse gases, air pollutants, and chemical substances to the marine environment. In particular, the roughness condition of underwater surfaces of a ship hull affects the ship's energy efficiency, with marine growth (biofouling) and mechanical roughness leading to propulsion powering penalties. Measures to control biofouling, using antifouling coatings and in-water hull cleaning, may also be associated with significant impacts to the marine environment. In the current study, a new tool is presented, HullMASTER (Hull MAintenance STrategies for Emission Reduction), which aims at enabling the shipping industry and authorities in the Baltic Sea region to make evidence-based decisions on hull maintenance strategies. HullMASTER simulates emissions to air and water, to calculate the differences in economic cost for operators, as well as health- and environmental damage costs between different hull maintenance scenarios. Validation of HullMASTER predictions against 40 vessel-years of in-service performance data on propulsive performance, with operations in the Baltic Sea region, shows good agreement, averaging within 5 percentage-point difference in propulsion penalty. Further, a scenario-based demonstration of HullMASTER on a general cargo vessel shows that, in the comparison between a silicone foul-release coating and business-as-usual scenario of a biocidal coating, retrofitting the coating to a foul-release coating can result in significant savings for society, i.e., along with marginal savings in cost for ship operators. Results for such comparisons and analysis will however be dependent on specific vessel cases and operational profiles, thence the value of an interactive tool such as HullMASTER.



**Keywords:** maritime transport; biofouling; antifouling coating; energy efficiency measures; marine environment; chemical pollution.

# 1. Introduction

Maritime transport is facing significant challenges to decarbonize. By 2050, the International Maritime Organization (IMO) projects greenhouse gas (GHG) emissions from shipping to reach 90-130% of 2008 levels (IMO, 2020), which fall short or in opposition to IMO's ambition of 50% reduction by 2050 (MEPC, 2019). Shipping is also responsible for a significant share in air pollution (Sofiev et al., 2018) and emission of chemical substances to the marine environment, affecting human health and marine ecotoxicity, respectively.

Low-friction hull coatings and hull maintenance are listed under abatement technologies to reduce carbon dioxide ($CO_2$) emissions from shipping (IMO, 2020). Maintaining a ship hull as smooth as practical, by reducing coating roughness and inhibiting marine fouling, leads to significant fuel and air emission savings (Schultz, 2007a). Marine fouling on ship hulls also represents a risk of spread of invasive aquatic species (Gollasch, 2002). At the same time, most commonly used antifouling coatings prevent biofouling by releasing chemically active substances (Amara et al., 2018). Copper (Cu) and zinc (Zn) biocidal compounds are the most widely used antifoulants in shipping, and these contribute to negative trends in ecological status in the Baltic Sea (Jalkanen et al., 2021).

In order for shipowners to select the most sustainable hull maintenance strategies, there is a need to compile and communicate available evidence on economic performance and societal impact of different technologies in form of Life Cycle Cost analysis (LCC). Previous studies have looked at economic and environmental trade-offs of in-water hull cleaning, IWHC (Pagoropoulos et al., 2018), and life cycle comparison of biocidal versus non-biocidal coatings (Demirel et al., 2018). Combined with models for fouling growth (Uzun et al., 2019a), it has been possible to calculate $CO_2$ emissions from both operation and hull maintenance (Uzun et al., 2019b). The benefits of applying low-roughness antifouling coatings have also been analyzed from the sole perspective of greenhouse-gas emissions (Farkas et al., 2021). However, to the best of the authors' knowledge, no study has yet provided estimates on emission uncertainties to conclude on statistical significance of comparisons between different hull maintenance scenarios in shipping. Also, in light of a recent valuation framework on societal costs of shipping (Ytreberg et al., 2021), a decision-support tool that compiles existing and new data on environmental and economic performance of hull maintenance strategies is called for.

The aim of this paper is to describe, validate and demonstrate an 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 shipowners, charterers and public authorities to compare hull maintenance strategies in terms of costs for operators, as well as to health and environment.

HullMASTER encompasses both shipping-operator costs, as well as societal costs. Thus, HullMASTER enables authorities and other stakeholders to weigh externalities (societal costs) against economics of hull maintenance.

The current approach follows previous studies (Bebić et al., 2018; Uzun et al., 2019a) and currently adds a more comprehensive list of externalities (Ytreberg et al., 2021). The current scope is limited to vessels operating in the Baltic Sea region, even though the framework is more widely applicable.

In demonstrating HullMASTER for a representative vessel, the hypothesis is tested on whether retrofitting from a conventional biocidal antifouling coating to a non-biocidal coating would provide economic and/or societal savings. Thus, alternative coating types, namely a foul-release coating that relies on low fouling-adhesion properties and an inert abrasion-resistant coating (the latter combined with IWHC) are compared to the conventional approach of using a biocidal antifouling coating.

# 2. Materials and methods

## 2.1. Scope and software

### 2.1.1. Goal & Scope

The goal of the current tool, HullMASTER, is to enable LCC analysis comparisons between different hull maintenance scenarios for a single ship and route in the Baltic Sea region, in terms of economic cost, and social & environmental impact in order to identify the most sustainable strategy. The functional units used are annual average cost difference between scenarios for a given ship, in €/year. HullMASTER's range of application reaches beyond local vessel management, being also of interest for public authorities who need to weigh impacts of measures or policies on vessels operating under their jurisdiction.

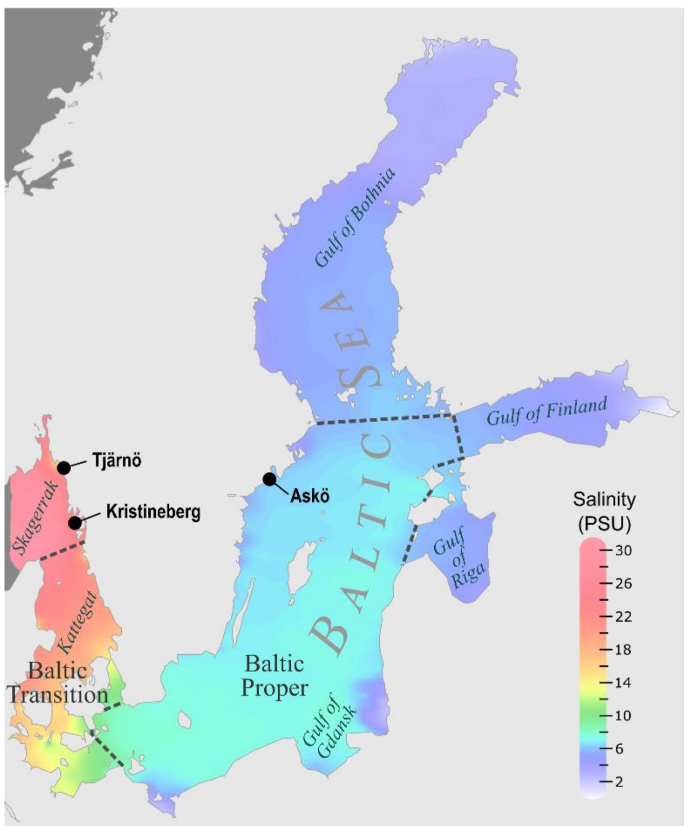



*Figure 1 – Current geographical scope of the Baltic Sea region, including Baltic Proper, Baltic Transition, and Skagerrak Sea, with location of 3 marine stations for collection of fouling data: Tjärnö, Kristineberg and Askö.*

The focus of the analysis is on local emissions occurring in the Baltic Sea region, including Baltic Transition and Skagerrak Sea (Figure 1), during the life phases of an underwater ship hull coating due to its application and its maintenance. Emissions related to upstream activities such as the production of the paint and its transportation to the dry dock are therefore not considered. Figure 2 illustrates the different identified phases in the lifetime of a hull coating on a ship hull included in the current analysis, from first paint application to complete paint removal in dry dock (DD). The latter lifetime of the coating on a hull, from first application to complete removal, constitutes the scope in time for LCC analysis in HullMASTER.

### 2.1.2. Inventory analysis

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 were identified (Figure 2). As described in more detail in 2.2., the energy consumption and resulting emissions from a ship are modelled in HullMASTER using a hydraulically smooth ship as the reference point. Thus, only costs and emissions occurring due to increased exhaust gas as related to increased hull roughness compared to a smooth hull were considered, neglecting other components of cost and emissions of operating a ship, which remain constant between different hull maintenance scenarios. As shown in Figure 2, only the air and water emissions caused by the energy penalty and due to the operation of engine and eventual water emissions from a scrubber, installed for removing sulfur oxides from the engine's exhaust (Exhaust Gas Cleaning System), were thus considered in each scenario.

Figure 2 also illustrates current delimitations in terms of types of emission and costs in HullMASTER, with text in grey italic indicating current exclusions. Some costs were excluded, which need to be evaluated on a case-by-case basis by the operators, namely eventual vessel off-hire costs, revenue loss, inspection costs, and transportation costs to/from maintenance locations. Additionally, biosecurity issues, i.e. the transport of non-native invasive species, are currently excluded, due to high complexity involved and existence of tools that are better suited for the purpose, namely conceptual Bayesian networks (Luoma et al., 2021). Emissions during dry-docking maintenance, namely during paint application and paint removal, were excluded, as their impact may differ among different suppliers, depending on technical solutions in place (Schulz and Pastuch, 2003). Finally, although not depicted in Figure 2, indirect emissions associated with dry docking or IWHC activities were not included: emissions during the use phase of the coating have been observed to far outweigh those of the application and removal phases (Uzun et al., 2019b).

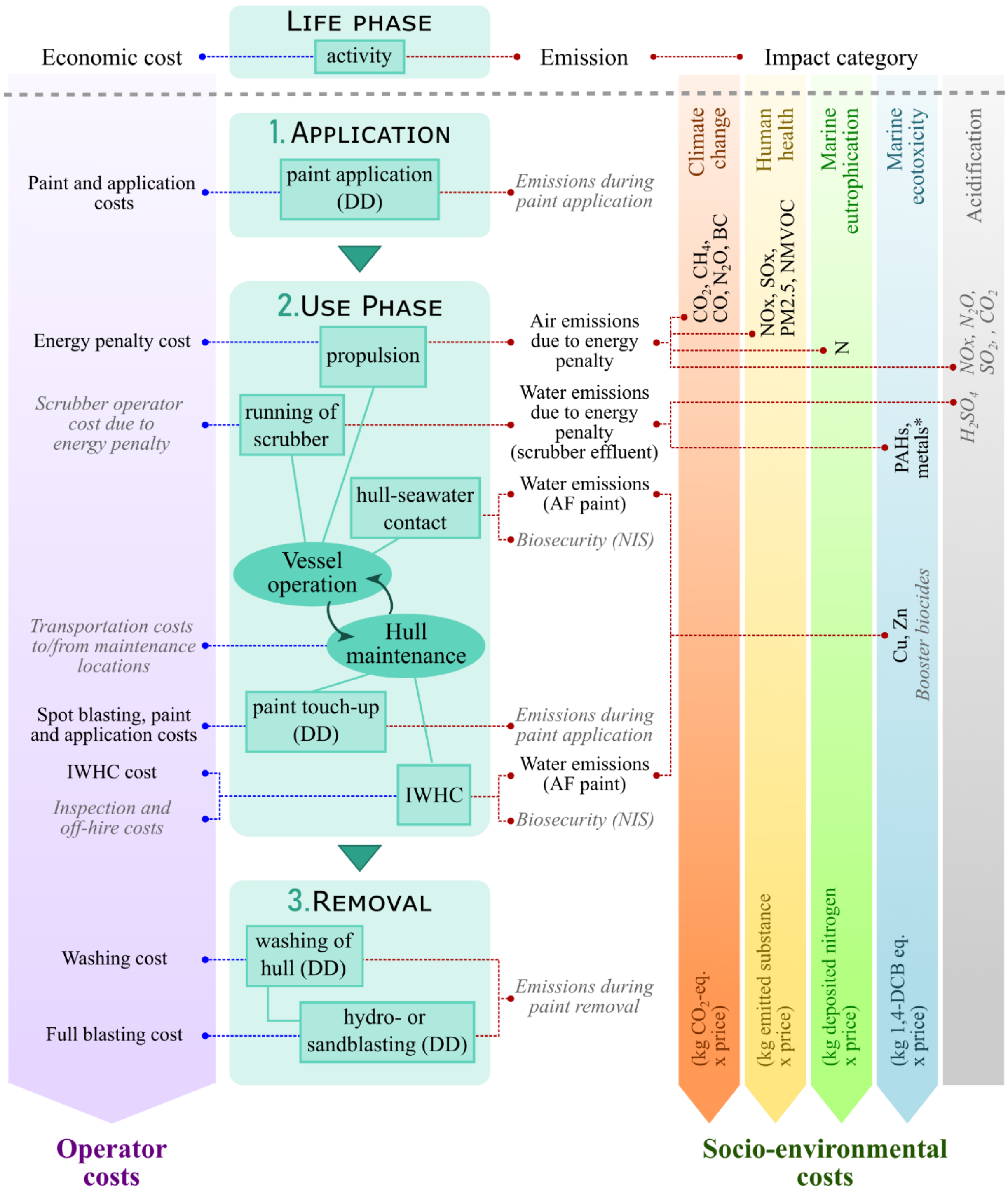



*Figure 2 – Economic costs and emissions considered in HullMASTER. Components excluded from analysis are given in grey italic text. For the complete list of metals emitted in scrubber effluent, see (Ytreberg et al., 2021). Abbreviations: DD – dry docking; IWHC – in-water hull cleaning; AF – antifouling; BC – black carbon; NIS – non-native invasive species; NMVOC – non-methane volatile organic compounds; PAHs – poly-aromatic hydrocarbons; PM2.5 – fine particulate matter.*

#### 2.1.3. Impacts and cost assessment

Different emission of substances contributes to particular impacts on society and the environment, as depicted in Figure 2 by vertical arrows on the right-hand side. For every emission category (e.g. air emissions due to energy penalty), the emitted substance(s) (e.g. $CO_2$) were sorted into relevant social and environmental impact categories (e.g. climate change). A total of five impact categories were identified, namely climate change, human health, marine eutrophication, marine ecotoxicity and acidification. These externalities are expressed as damage pricing in € / quantity of emitted substance. Acidification is not currently included due to lack of data for the current geographical scope, Baltic Sea region (Ytreberg et al., 2021).

Societal and environmental damage cost valuation is based on previous work (Nordhaus, 2017; Noring, 2014; Noring et al., 2016; Ytreberg et al., 2021). Pricing assumptions are detailed and listed in the *Supplementary Materials: Economic Social and Environmental Valuation (pricing),* under "ENVIRONMENT". Pricing uncertainties are expressed as 95% confidence intervals.

Human health impacts are valuated according to Value Of Life-Years lost, VOLY, specifically developed for the Baltic Sea region (Ytreberg et al., 2021). Carbon emissions, in $CO_2$-equivalents and emissions of nitrogen oxides (NOx), sulfur oxides (SOx, in $SO_2$-equivalent), fine particulate matter (PM2.5) and non-methane volatile compounds (NMVOC) are accounted for in terms of increased exhaust gas on a rough hull, compared to a smooth hull (energy penalty). Climate impacts are valuated according to recently-revised social cost of carbon (Nordhaus, 2017). Marine eutrophication pricing, in $€_{2020}$ / kg N emitted, was derived from Ytreberg et al (2021) and are site-specific for the Baltic Sea region. In the valuation, nitrogen deposition is assumed to be 18% of the total emitted nitrogen in a given sub-basin, i.e. 18% of total NOx emissions (Ytreberg et al., 2021).

Marine ecotoxicity costs include, on the one hand, the environmental cost of emitting heavy metals from antifouling coatings (Cu and Zn) and, on the other hand, increased emission of scrubber water to the marine environment for scrubber-fitted vessels, the latter related to propulsive penalties associated with hull roughness. Most vessels today have their hulls painted with biocidal antifouling coatings, which inhibit marine fouling through releasing biocides (most commonly copper-containing biocides) in contact with seawater (Lindholdt et al., 2015). Most paints also contain zinc oxide in order to control the erosion of the paint, resulting in a release of Zn to the marine environment (Lagerström et al., 2018). HullMASTER includes time-series modelling of Cu and Zn release rates (see 2.2.2). Other biocides, so-called "booster biocides" (e.g. DCOIT, dichlorooctylisothiazolinone), are not currently addressed due to lack of compatible data.

Emission of Cu and Zn from coatings are valuated based on ReCiPe characterization factors for marine ecotoxicity (1,4-Dichlorobenzene equivalents, 1,4-

DCB eq. emitted to seawater) and damage costs in form of willingness-to-pay for measures to improve the marine environmental status, in €/kg 1,4-DCB eq. (Noring, 2014; Noring et al., 2016), to obtain the valuation per emitted kg of Cu or Zn. Similarly, for scrubber emissions, values of kg 1,4 DCB-eq / $m^3$ of scrubber wastewater are multiplied by the damage cost of 1,4-DCB to obtain the environmental cost of emitting scrubber water, in €/$m^3$ of scrubber wastewater. Current characterization factors, as well as damage cost for 1,4-DCB, are listed in detail in *Supplementary Materials: Characterization factors and damage costs.* Uncertainties in characterization factors and damage cost are propagated by multiplying 95% bounds for characterization factors with respective bounds for damage cost.

Finally, economic costs for operators include paint application and maintenance costs (including hull surface preparation: washing and spot-/full-blasting of the hull), increased energy-consumption costs due to hull roughness (energy penalty), and IWHC costs. Further details on assumed default pricing for operator costs are included in *Supplementary Materials: Economic Social and Environmental Valuation (pricing).*

#### 2.1.4. Software,availability and output format

HullMASTER is implemented in Matlab® App Designer (version R2019b, MathWorks, Natick, MA, USA) and the tool is deployed as a standalone Windows application. The app is made available in the Supplementary Materials to this article and consist of a user interface for input selection and user-defined parameters. Results are plotted as time series and bar plots for cost difference between a given scenario and a business-as-usual (BAU) scenario, as well as in tabular format, which can be exported as ".csv" files. Users can also save their scenarios in local folders and load these at a later stage. Scenarios are saved locally as ".mat" files, formatted specifically for HullMASTER. For a programmatic and user-interface overview of HullMASTER, please refer to *Supplementary Materials: Tool Flowchart and User interface*.

### *2.2. Emission models*

In this section, HullMASTER's required input, main assumptions, and models are described in more detail, which are schematically summarized in Figure 3.

#### 2.2.1. Required input parameters

A minimum user input is required to build a scenario, including vessel details, fuel type and properties, engine properties, exhaust after-treatments, activity pattern, route details, and maintenance options within the paint's lifetime (i.e. from first application to complete paint removal).

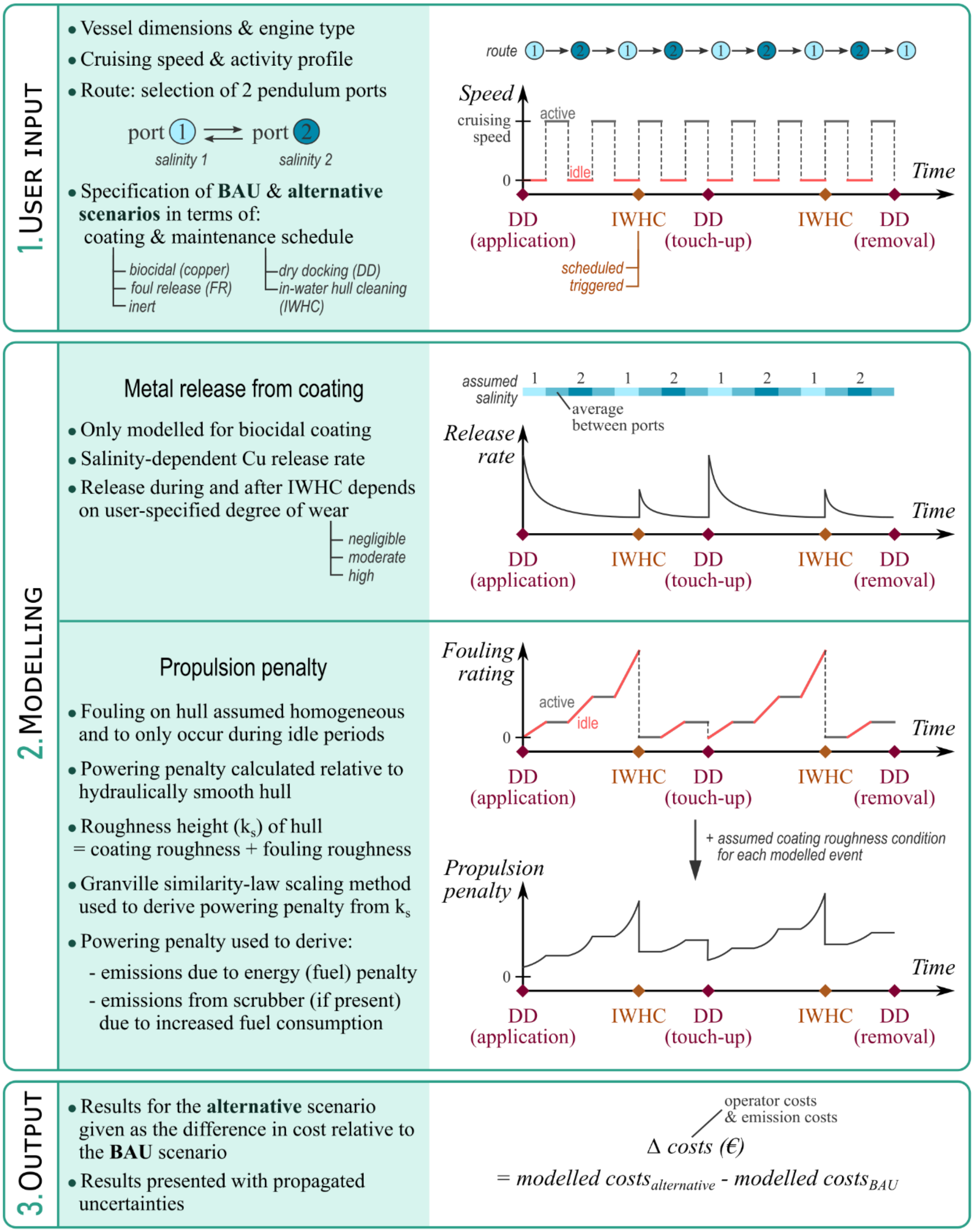



*Figure 3 - Schematic overview of required input, main assumptions, and modelling concepts of HullMASTER. Tree structures show some of the variables available for selection in the tool. BAU – Business-As-Usual.*

Default vessel details, such as main vessel particulars are currently based on the list of vessel categories used by the International Maritime Organization's (IMO) 4th greenhouse gas (GHG) study (Table 35 of IMO, 2020), please refer to *Supplementary Materials: list of default vessels*. Vessel parameters are manually editable by the user.

In order to adequately account for emissions to the atmosphere and fuel costs, the user selects/confirms fuel type, sulfur content, engine manufacture year, engine stroke, engine speed (rpm) and exhaust gas after treatment (scrubber details, and NOx-reduction techniques). Further, HullMASTER prompts the user for a description of typical activity profile and route details, as well as any additional one-off idle periods. A typical activity profile is defined by intermittent periods of activity, i.e. a typical active period [days] in which the vessel is assumed to travel at an average cruise speed [knots], spaced by typical idle periods [days], i.e. null vessel speed (Figure 3, under *User Input*). The vessel is assumed to travel between two main port with representative seawater properties (average salinity and temperature), which are converted to seawater density and viscosity. Finally, indication of navigation in ice limits available coating selection to an inert abrasion-resistant coating.

#### 2.2.2. Emissions from antifouling coating

Cu and Zn emissions are modelled based on the studies of (Lagerström et al., 2020) for average release rates in Baltic Sea region, and (Valkirs et al., 2003) for modelling the long-term decrease in release rates. For a detailed description of the current release rate model ("passive" excludes emissions during in-water hull cleaning), please refer to *Supplementary Materials: release rate model*.

The cumulative emission of Cu and Zn is expressed as:

$$Total\ Cu\ (or\ Zn)\ emissions\ [kg] = S \times \sum_{i=1}^{N} \left[ RR_{t_i} * (t_i - t_{i-1}) \right]$$

*Equation 1*

where *S* is wetted surface area [$m^2$], $RR_{t_i}$ is release rate [kg/$m^2$/day] on time step $t_i$, *N* is total number of simulated points, and *i* is the time-step index. Furthermore, coating depletion is tested at each point in time, by a mass balance, and the coating is rendered inert after depletion, i.e. behaving as an inert coating in regard to fouling growth.

Uncertainties in the biocide emission model include replicate variability and correlation uncertainty between release rate and salinity. Error propagation results in 95% confidence intervals expressed in final release rates.

#### 2.2.3. Fouling growth model

Hull fouling condition is defined here based on US Navy's fouling rating, $fr_{NSTM}$ (Naval Sea Systems Command, 2006a; Oliveira and Granhag, 2020). Fouling rating is reported in a 0-100 scale, where zero represents a clean coating and 100 represents the presence of all types of fouling, both soft and hard advanced forms of fouling (*Supplementary Materials: US Naval Ships' Technical Manual fouling rating*). This fouling-rating scale has been previously used in translating fouling conditions to estimates of ship propulsion penalty (Demirel et al., 2019; Schultz, 2007b; Song et al., 2020), which is a prerequisite for current calculations on energy penalties.

Predicting the amount of fouling that grows on a given hull is a complex task, dependent on a myriad of factors (Uzun et al., 2019a). The two best predictors for fouling growth rate in the Baltic Sea region are (1) cumulative idle time (Oliveira and Granhag, 2020) and (2) salinity (Wrange et al., 2020).

Fouling data was collected in a parallel study (Lagerström et al., 2021), in which painted panels were immersed under idle condition at 3 locations around Sweden: Tjärnö (26 psu), Kristineberg (23 psu), and Askö (salinity 6 psu, see map in Figure 1). Acrylic panels with dimensions 15-by-15 cm were sanded and then painted with a roller, with a first layer of primer, followed by a top coating (Table 1). Additional panels were left with only the first layer of inert primer to assess the performance of an inert coating. Quadruplicates were used for each treatment. Panels were deployed in July 2020, at a depth of 1-2 m, and inspected on a monthly basis for a total period of up to 1 year. Results from the two biocidal copper coatings were not statistically different, so these results were pooled before curve fitting in HullMASTER, using areal-averaged fouling rating as described in *Supplementary Materials: calculation of areal-averaged fouling rating.* Due to the limited number of locations, linear interpolation for salinity between locations was deemed the most adequate approach to determine fouling growth rates at a chosen location, an approach which was suitable across all coating types.

*Table 1 – Paints used in the reference fouling growth field study (Lagerström et al., 2021). DCOIT – 4,5-dichloro-2-octyl-isothiazolone.*

| Coating type | Product name | Manufacturer | $Cu_2O$ (wt%, ww) | ZnO (wt%, ww) | Copper pyrithione (wt%, ww) | DCOIT (wt%, ww) |
|---|---|---|---|---|---|---|
| Inert coating | Underwater Primer 26030 | HEMPEL® | 0 | 0 | 0 | 0 |
| Biocidal copper coatings | SeaForce 60 | JOTUN® | 31.6 | 10-25 | 1.5 | 0 |
| | Sigmarine 530 | PPG® | 39.02 | 10-25 | 0 | 2.53 |
| Foul-release | SILIC ONE | HEMPEL® | 0 | 0 | 0 | 0 |

In HullMASTER, panel data for average fouling rating versus immersion time is fitted as exemplified in Figure 4, using Gaussian function (Uzun et al., 2019a):

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

*Equation 2*

where $t_{idle}$ is the cumulative idle time [days], and *a, b* and *c* are fitted parameters. Fitted curves according to Equation 2**Error! Reference source not found.** are then re-sampled for linear interpolation based on user-selected seawater salinity in a given port of call, using fouling observations from panel-deployment stations encompassing the average salinity at each port of call, or the closest conditions representing the selected port salinity (no extrapolation for extreme salinity values >26 psu or <6 psu: the closest data is used instead), as exemplified in Figure 4 for a simulated location, "Port of call" (14.5 psu).

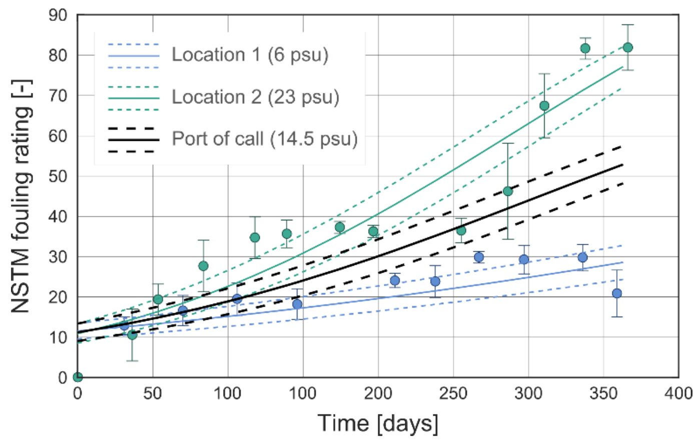



*Figure 4 – Example of US Navy fouling rating (NSTM) time series for 2 locations (field data, areal averages), and linear interpolation based on salinity for a third location, "Port of call". Average values for field data are given as circles, and the 95% confidence intervals is represented by error bars (field data), and by dashed lines (fitted and interpolated curves).*

Finally, using the above linearly-interpolated fouling growth curves, the change in fouling rating during a particular idle period is calculated as:

$$\Delta\, fr_{NSTM}(t_i) = \frac{d\, fr_{NSTM,\text{port of call}}(t_{idle,i})}{d\, t_{idle}} \times\ \Delta t_i$$

*Equation 3*

where $t_i$ is the elapsed time since start of operations (in days), $t_{idle,i}$ is the cumulative idle time (in days), $d\, fr_{NSTM,\text{port of call}}$ / $d\, t_{idle}$ is the fouling growth rate, and $\Delta t_i$ is the duration of the idle period *i*. Further, for hulls subject to in-water cleaning, fouling growth rates are reset to out-docking coating performance at the time of the cleaning event. Further, two optional in-water hull cleaning triggers are included in HullMASTER, a cleaning trigger based on U.S. Navy fouling threshold criteria (I), and a cleaning trigger based on a maximum propulsive power penalty set by the user (II). Cleaning trigger I inserts a cleaning event whenever confidence intervals for fouling rating reach $fr_{NSTM}$ = 40 for biocidal copper or inert coating), or $fr_{NSTM}$ = 50 for a foul-release coating (Naval Sea Systems Command, 2006b).

Uncertainty estimates for fouling growth include panel replicate variability, seasonal variations, and correlation uncertainty between fouling pressure and salinity. Error propagation results in 95% confidence intervals expressed in fouling growth rates.

### 2.2.4. Emissions due to hull-roughness energy penalties

Once hull fouling accumulation has been determined over time, this will be converted, into a hull-roughness propulsion penalty, together with an estimate of initial coating roughness, for calculating cost and emission differences between scenarios.

In HullMASTER, the user selects coating type and surface preparation in dry-dock. This input is used for selecting initial coating roughness. Hull condition is then expressed in equivalent sand-grain roughness height, $k_S$. Initial roughness height assumptions are derived from previous literature (Schultz, 2007b; Yeginbayeva and Atlar, 2018) and a public-access skin friction database (Leer-Andersen, 2018). Assumptions are summarized in *Supplementary Materials: initial coating roughness conditions*.

Adding to this initial coating roughness height, hull fouling condition (see section 2.2.3) is also converted into an estimate of roughness height $k_S$, which is modelled according to estimates given in (Schultz, 2007b) by fitted curve ($R^2$ = 0.96):

$$k_{s,fouling}(t) = 46.927 \times e^{0.056614 \times fr_{NSTM}(t)}$$

*Equation 4*

where $k_{s,fouling}$ is equivalent sand roughness height due to fouling [µm] and $fr_{NSTM}$ is the hull fouling condition (fouling rating). Finally, the *change* in roughness height due to accumulation of fouling is summed to the initial hull coating’s hydraulic roughness height.

Propulsion penalties are calculated based on roughness height $k_S$ (coating + change due to hull fouling) using Granville similarity-law scaling method. The Granville method relies on friction lines for flat plates, which are shifted based on a roughness function, i.e. the effect of roughness on the boundary layer velocity profile. The method is described and validated in more detail elsewhere (Demirel et al., 2017; Oliveira et al., 2018; Song et al., 2021). The Granville method yields towing resistance penalty due to hull roughness $\Delta R$ [kN], which is then converted into powering penalty $\Delta P$ [kW], assuming a negligible effect on propulsive efficiency $\eta_D$ (Oliveira et al., 2020):

$$\Delta P(t)\ [\mathrm{kW}] = \frac{\Delta R(\ k_s(t)\ )[\mathrm{kN}] \times \mathrm{V}[\mathrm{m/s}]}{\eta_D[-]}$$

*Equation 5*

where $V$ corresponds to the vessel speed [m/s].

Finally, the above $\Delta P$ is added to baseline smooth-hull power consumption $P_{smooth}$, yielding the rough hull powering $P_{rough}$:

$$P_{rough}(t) = P_{smooth}(t) + \Delta P(t)$$

*Equation 6*

Modelling uncertainties are currently unavailable for the Granville method. Uncertainties from initial coating roughness height and fouling growth model are however propagated into $\Delta P$ and $P_{rough}$. In order to validate these powering penalties, hull-and-propeller performance is analyzed as described in more detail in *Supplementary materials: validation of hull roughness penalties*. The aim of such validation is to compare predicted powering penalties against measured performance from onboard-collected data in terms of percentage of smooth hull powering:

$$P_{diff}[\%] = \frac{P_{measured} - P_{baseline}}{P_{baseline}} \times 100 = \frac{\Delta P}{P_{baseline}} \times 100$$

*Equation 7*

where $P_{measured}$ is the measured propulsion power (shaft power) and $P_{baseline}$ is the baseline calm-water propulsion power for a smooth hull, both in kW.

#### 2.2.5. Emissions factors for air emission and scrubber

Emission factors are required in order to translate a given propulsive power penalty into environmental loads. For more details, please refer to *Supplementary Materials: Emission Factors.*

### *2.3. Demonstration examples*

For demonstration of HullMASTER and testing the hypothesis of economic and societal savings from retrofitting a vessel from a conventional biocidal coating to non-biocidal coatings, a reference vessel is selected, as well as two routes, each in the Baltic Proper and Baltic Transition (see definition of Baltic Transition on Figure 1, which includes Kattegat Sea and the Danish Straits).

Dry cargo vessels are the largest single contributor to antifouling biocide emissions in the Baltic Sea region, being also among the top three emitters of $CO_2$, together with RoPax and tankers (HELCOM, 2019). A 10,000-deadweight general cargo vessel is thus selected (Figure 6**Error! Reference source not found.**A – vessel specifics), based on median of main engine power for vessels with domicile, control or registration in Baltic Sea countries (IHS Markit, 2020). Vessel specifics are given in Figure 6**Error! Reference source not found.Error! Reference source not found.**A, and the vessel operates a route in the Baltic Sea Proper, with low port water salinity (Karlshamn-Klaipeda, salinity 2-7 psu), or in Baltic Transition, with higher salinity (Gothenburg-Kiel, 14-19 psu).

Three maintenance scenarios are simulated for each route, where Scenario 0 is the BAU scenario of a conventional TBT-free polishing copper biocidal antifouling coating, with complete coating removal every other docking (Gundermann and Dirksen, 2016), whereas Scenarios 1 and 2 correspond to biocide-free foul-release and inert coatings, respectively, which have an assumed longer lifetime of 10 years (Kowalski, 2020), even though the lifetime of inert coatings can be higher (Rompay, 2013). For the inert abrasion-resistant coating (Scenario 2), which has no fouling-control properties, an in-water cleaning trigger is included, based on US Navy criteria (cleaning trigger I, as described in section 2.2.3). All hull coatings are subject to touch-up maintenance at least once in their lifetime (Figure 6A), during which the hull is partially sand-blasted, on 5-10% of its wetted surface area, prior to paint application (full re-coating for biocidal copper paint, and patch-painting for foul-release and inert paint types), see further default pricing assumptions in *Supplementary Materials: Economic Social and Environmental Valuation (pricing).*

# 3. Results and discussion

## *3.1. Validation of powering penalties*

Nearly 40 vessel-years of in-service performance data, represented as time series of propulsion powering penalty [%] in Figure 5, for each vessel A-I, are used here for validating HullMASTER predictions of propulsion powering penalties against measured performance for a fleet of 9 vessels.

In Figure 5, time series of propulsion powering penalties are given both for HullMASTER predictions and measured propulsion penalties. It should be noted that the latter are not modelled in HullMASTER, so no decrease in penalties occurs within the predictions. Under Figure 5J, differences between predicted and measured penalties are summarized as bar plots, indicating average and statistical significance of differences between predictions and measurements.

From Figure 5J, it can be seen that predictions deviate on average less than 5 percentage points for most vessels. Exceptions are vessels D (-5.8%) and H (-15.0%), which along with vessel I, also deviate significantly from a null difference between predictions and measurements. These vessels show underprediction by HullMASTER, alternatively overestimation in measured propulsion penalties (Figure 5: D, H, and I). Examples of such underprediction (or overestimation in measurements) are observed especially for vessels H and I, which were retrofitted to a silicone foul-release coating after the first dry-docking (see vessel particulars in *Supplementary Materials: validation of hull roughness penalties)*. This could indicate that silicone coatings applied might not be as smooth as assumed in HullMASTER (Leer-Andersen, 2018; Yeginbayeva and Atlar, 2018), or unaccounted changes in vessel displacement (vessels D and H did not report draft) or in engine performance (vessel I reported fuel consumption as a proxy for shaft power).

Overall, HullMASTER predictions show good agreement with measured propulsion penalties across a fleet of 9 vessels, with an average of difference between HullMASTER predictions and measurements of -3.2 ± 3.8 percentage points (n = 9 vessels), which indicates marginal underprediction of propulsion penalties.

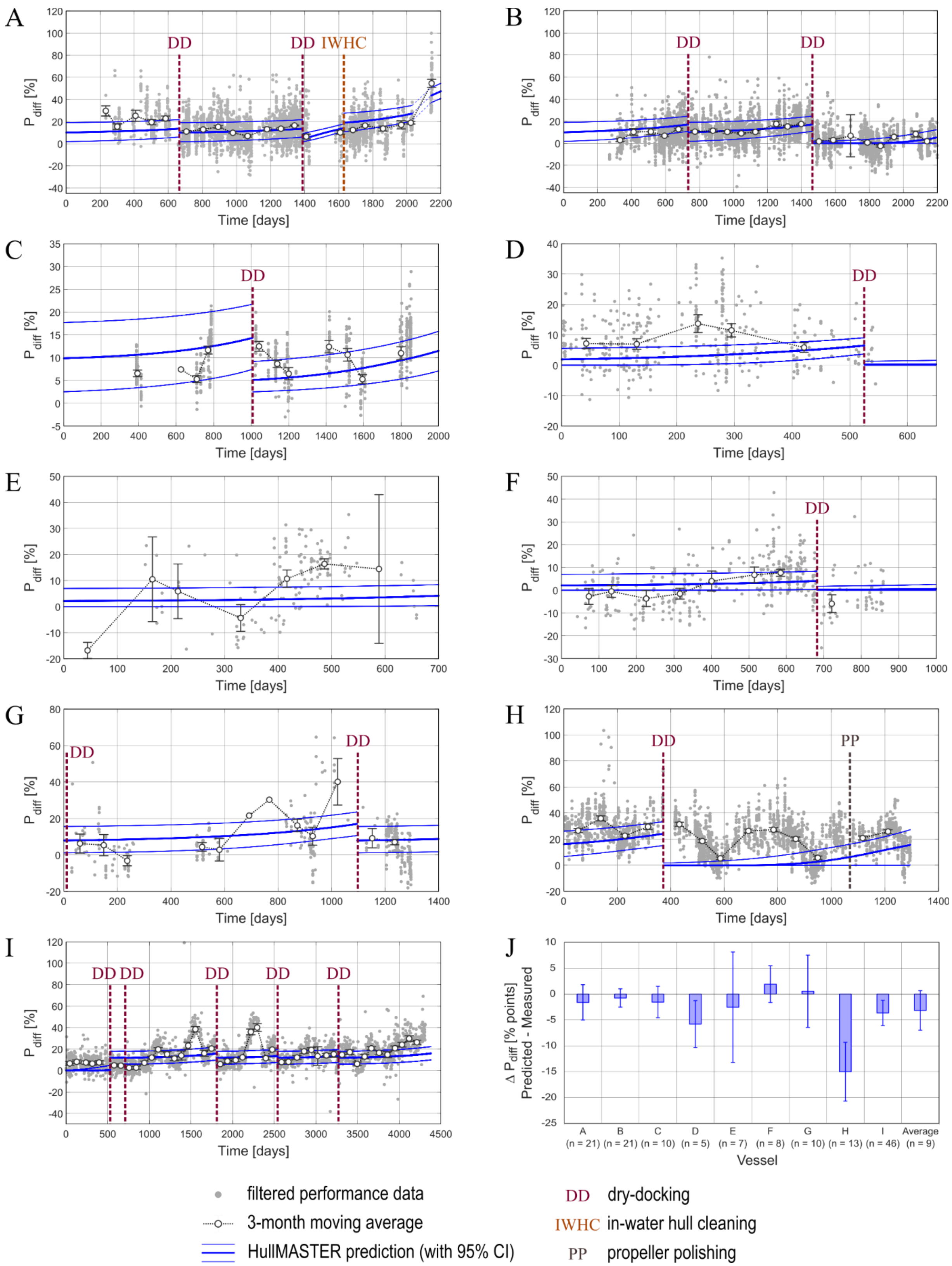



*Figure 5 – Validation of HullMASTER predicted hull performance against measured filtered performance data for 9 vessels (~40 vessel-years), expressed as percentage power penalties* $P_{diff}$ *versus time, together with statistical comparisons across the fleet (J). All error bars correspond to 95%-confidence intervals with* n-1 *degrees of freedom.*

## *3.2. Demonstration of scenario-based approach in HullMASTER*

For demonstrating Life-Cycle Cost (LCC) analysis in HullMASTER, three coating types and maintenance schemes are evaluated on a representative median-powered general cargo vessel, as detailed in Figure 6**Error! Reference source not found.**A, in combination with two routes. Economic and societal costs are discussed here, and plots of intermediate variables are included in *Supplementary Materials: Intermediate results.*

Cost-difference results are presented in Figure 6B, top bar plots. Statistically significant socio-environmental cost savings in order of ~250k €/year can be achieved in Baltic Transition with a foul-release coating (Scenario 1) compared to a biocidal copper coating, Scenario 0 (Figure 6B, Route A). Marginal cost differences are observed for an inert coating (Scenario 2), where uncertainties are larger than cost differences. Marginal differences are also observed for all scenarios in Baltic Proper, 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 operators, using a foul-release coating would result in an average, yet not significant, marginal cost saving of ~20k €/year in the Baltic Transition (Figure 6B, Route A) or ~15k €/year in the Baltic Proper, which are somewhat lower 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.

Further decomposition of costs is illustrated in Figure 6B, bottom bar plots, for both operator and societal costs. For operators (Figure 6B, purple bars), it is observed that the largest cost differences are associated with hull-roughness energy penalty costs (bunker fuel), with hull maintenance representing only 5-15% of the cost difference for operators. Fuel costs still have large confidence intervals mainly due to uncertainties in hull roughness modelling (initial coating roughness + fouling roughness). Maintenance costs are almost identical among coatings, in spite of initial higher investment for foul-release and inert coatings (30-50 €/m$^2$) compared to antifouling (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<br>132.2 m length, 10,000 DWT<br>3332 $m^2$ wetted surface area | Idle time: 40%<br>(0.5 days idle, 0,8 days sailing)<br>Average cruise speed: 12 knots | Ultra Low Sulphur Fuel Oil (0.07% Sulphur)<br>No scrubber<br>No NOx abatement |

Maintenance scenarios:

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

B. Cost difference compared to baseline scenario

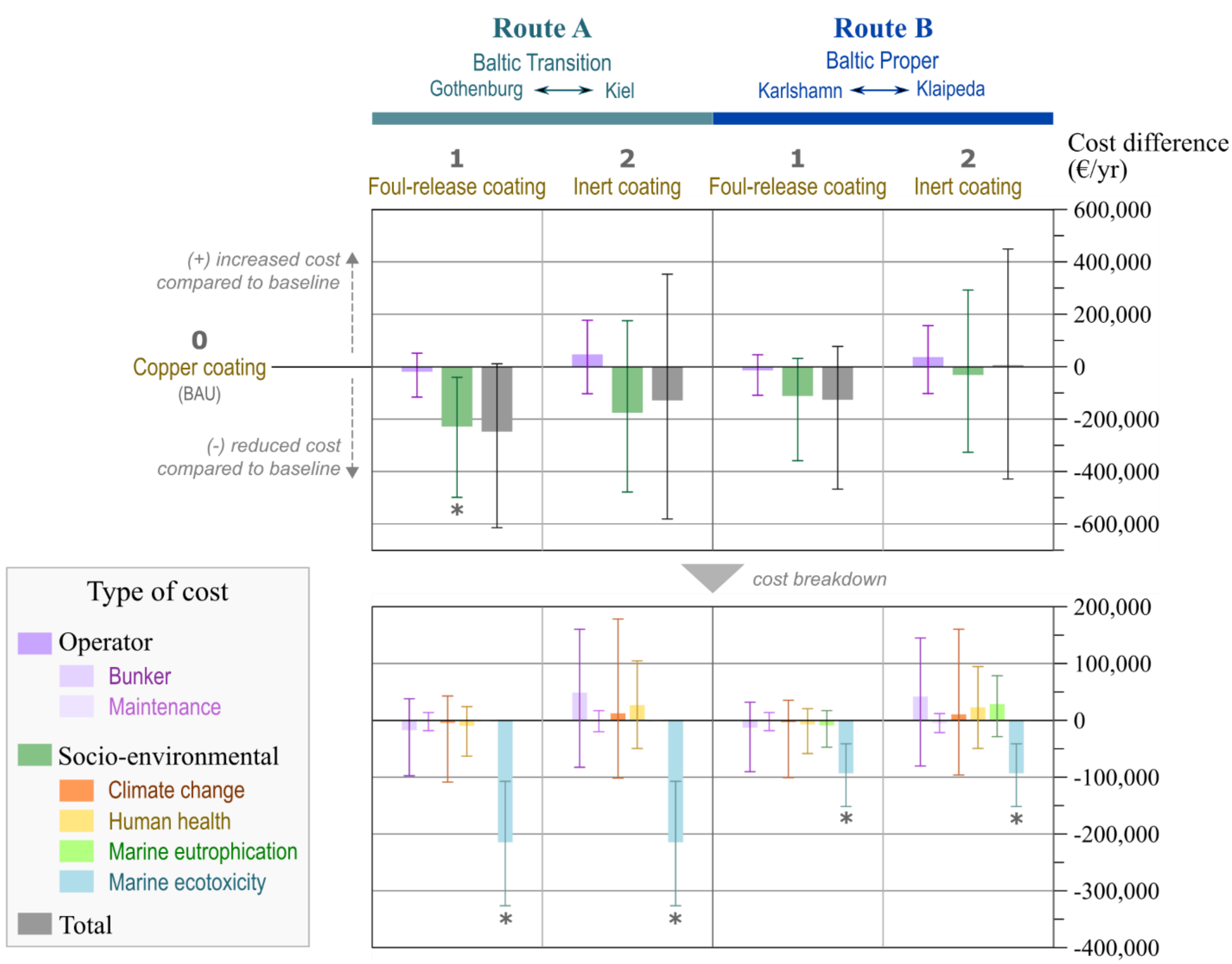



*Figure 6 - Demonstration example for HullMASTER: A – Input: main parameters; B – Output: cost difference. Asterixis show significant cost differences compared to BAU (Business-As-Usual).*

Clear societal savings are achieved in regard to marine ecotoxicity (Figure 6B, light-blue bars) by choosing foul-release or inert coatings (Scenarios 1 and 2) instead of the biocidal copper coating (Scenario 0), due to avoided copper and zinc emissions. No demonstration scenarios are presently simulated for in-water hull cleaning on biocidal copper coatings. In HullMASTER, in-water cleaning on a copper coating would lead to emission of 0, ~2100, or ~6400 µg Cu /cm$^2$/event, respectively for negligible, moderate, or high coating wear. These values encompass the range of previously reported values of ~3 µg Cu /cm$^2$/event (Soon et al., 2021a, sampling on 4 vessels), ~30 µg Cu /cm$^2$/event (Earley et al., 2014, ablative coating, non-BMP), and as high as ~30,000 µg/cm$^2$/event for more aggressive cleaning (Tribou and Swain, 2017, SCAMP).

A foul-release coating is associated with somewhat lower emissions to the atmosphere (Figure 6B, Climate change and Human health) due to lower coating roughness combined with inhibition of fouling, which is not the case for an inert coating, where an increase in emissions is noted. The latter is subject to in-water cleaning based on a U.S. Navy cleaning trigger, with a maximum fouling rating $fr_{NSTM}$ = 40, i.e. the lowest level of hard fouling. In-water cleaning and dry-docking cycles on inert coating are illustrated in Figure 7, where dry-docking occurs at 2-year intervals (730 days). In-water cleaning is automatically triggered based on fouling rating, yielding no in-water cleaning in Baltic Proper within a dry-docking interval of 2 years. This increases to one cleaning event per docking interval in Baltic Transition, reflecting higher fouling pressure in higher salinity. HullMASTER may thus be used also as a planning tool for scheduling and assessing the economics of in-water hull cleaning, provided that fouling or performance criteria are defined.

In this specific demonstration case, the hypothesis that retrofitting to non-biocidal coatings would result in societal savings, compared to biocidal copper coating, is thus proven for a foul-release coating in Baltic Transition, with marginal savings for operators. These results are based on the best available data for main types of coating in the Baltic Sea region. Marginal differences in cost are observed for all other scenarios (inert coating and Baltic Proper). Users of HullMASTER would then have to decide based on their criteria for risk assessment: in some cases it might be enough to decide based on marginal differences (non-significant), whereas in others a higher degree of confidence might be required, eventually achieved through improved assumptions defined by user input. Further, since the above vessel is not representative of the entire Baltic fleet, other vessels and operation profiles need to be evaluated on a case-by-case basis.

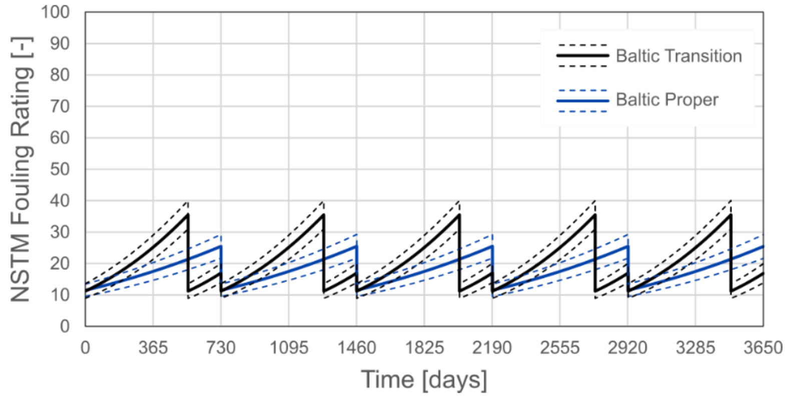



*Figure 7 – Demonstration of hull fouling rating for an inert abrasion-resistant coating in Baltic Transition and Baltic Proper. Dry-docking occurs every 2 years (730 days), and in-water cleaning is triggered whenever confidence intervals (dashed lines) reach a level of $fr_{NSTM}$ = 40 (tubeworms <6.4 mm in height, or encrusting bryozoans). Dashed lines represent prediction intervals at 95% confidence.*

## 3.3. Knowledge gaps and future development of HullMASTER

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 ice on fouling growth and coatings need to be further investigated, and so is the impact of other environmental conditions on both fouling growth and antifoulant release rates.

In what concerns the effects of vessel speed on fouling growth, fouling removal is expected to occur at a certain vessel speed, especially for foul-release coatings (Davidson et al., 2020). The current fouling model is based on fouling growth experiments performed under static conditions and hence follows a conservative approach of “no fouling removal”, and yet results still show good agreement with in-service measured performance, which could be due to either a too low fouling pressure in sampled locations (painted-panel study), or overestimation in measured hull roughness penalties (validation cases).

Further accuracy improvements in the fouling model could possibly be achieved by further increasing the amount of fouling data from panel studies, in a higher spatial and temporal resolution, capturing both local and seasonal effects, as well as accounting for effects of hydrodynamic forces, depth and surface orientation. Specifically, to build a more robust and accurate fouling growth model, more data at lower salinity (<6 psu) and higher salinity (>26 psu) would be needed. Navigation in ice may damage most-common antifouling and foul-release coatings and these cases have therefore been excluded from HullMASTER. More data is needed to evaluate effects of ice abrasion on both coating and fouling. Lack of data is noted also for fouling growth in the period subsequent to in-water hull cleaning events, which are currently assumed to reset the fouling growth curve (Gaussian function). Further, while it is the minimum salinity at each location that limits distribution of fouling species, HullMASTER uses yearly-average salinity as a practical (though approximate) predictor for fouling pressure, to which should be added other factors, namely seawater temperature (Uzun et al., 2019a).

Copper and zinc release rates are expected to be affected by temperature, flow and pH (Kiil et al., 2007), and these effects on today's biocidal copper coatings require further research and modelling. Further work is also needed for obtaining release rate data from vessels, to enable validation and determination of bias uncertainty in copper and zinc loading (Tamburri et al., 2020). Other biocides (booster biocides) might also be important to consider in future modelling efforts (Amara et al., 2018).

Future versions of HullMASTER could include improved power-speed curves for generic vessels beyond relying on a single approximate prediction method (see e.g. Tillig et al., 2018). In terms of measured penalties used for validation, precision accuracy and reliability of measured hull-and-propeller performance has also room for improvement, namely through acquisition of missing variables, calibration of sensors, improved baseline power-speed curves, and improved accuracy in environmental corrections (*Supplementary Materials: validation of hull roughness penalties)*.

Regarding modelling uncertainties, societal and economic costs related to energy penalties are still associated with large uncertainties, mainly in hull roughness models and pricing. As an example, confidence intervals for social valuation of carbon (Nordhaus, 2017) currently span nearly one order of magnitude, from ~22 €/ton to ~210 €/ton $CO_2$. Further research is needed into reducing uncertainties in pricing estimates, and improve initial coating roughness estimates, the latter relying e.g. on docking surveys. It should also be pointed out that the damage costs for marine ecotoxicity and marine eutrophication are site-specific for the Baltic Sea region and hence cannot be used directly for other sea areas. Similar studies are required to expand the tool to other sea areas around the globe.

Other aspects have been excluded from the current analysis, but could be considered in further research, such as upstream emissions (see e.g. Brynolf et al., 2014) and disentangling local, regional and global impacts. In HullMASTER, different emissions have either local (e.g. marine ecotoxicity), regional (e.g. human health), or global impacts (climate change). These impacts are expressed as societal costs, which are tied to total emitted quantities and regional willingness-to-pay studies. However, HullMASTER does not enable risk assessment on changes in local marine environment, namely modelling of changes in local water quality and risk spread of invasive species. Thus, future studies could look into how to couple HullMASTER results with modelling of Predicted Environmental Concentration (PEC), namely in shipyards (Soon et al., 2021b) and biosecurity risks related to hull fouling and maintenance (see e.g. Luoma et al., 2021).

# 4. Conclusions

Shipowners, charterers, and public authorities would benefit from an evidence-based decision support tool on the sustainability of hull surface maintenance strategies. HullMASTER is a tool developed to address this question, based on biocide release rate data, fouling growth on coatings under idle conditions, and pricing and societal valuation estimates developed for the Baltic Sea region.

Shipping operators can use HullMASTER as a complement to other calculation tools and customer requirements from shippers and charterers, compare return-on-investment to other sustainability initiatives, and find the most sustainable option according to their best available cost estimates. HullMASTER would also enable public authorities to draft measures and regulations that promote sustainability, using a more holistic approach.

Comparison to 40 vessel-years of in-service performance data shows good agreement with measured propulsion penalties across the current fleet of 9 vessels, with an average of difference between HullMASTER predictions and measurements of -3.2 ± 3.8 percentage points (n = 9 vessels).

In a demonstration case, foul-release coating stands out as the most sustainable approach for a 10,000-deadweight general cargo vessel operating in Baltic Transition (mid-range salinity). From the current results, societal cost differences (or change in externalities) are in the same or even higher order of magnitude as economic cost differences paid/saved by shipping operators, e.g. when retrofitting from a conventional biocidal copper coating to a biocide-free foul-release coating. savings to the marine environment come up at the top of the list as the single largest and most significant among societal impacts investigated in this paper.

Further research is needed for including effects of local hydrodynamics, temperature, depth, surface orientation, seasonality, and increased spatial resolution on the results. Additionally, in a life-cycle perspective, extending the scope of HullMASTER to include upstream emissions should be regarded as long-term goal, as well as extending the geographical scope towards worldwide shipping operations.

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