

THESIS FOR THE DEGREE OF DOCTOR IN PHILOSOPHY

Roughest hour – approaches to ship hull fouling management

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Cover:

Bow of a 200-m merchant vessel: portside view of the bulbous bow, exposed at low draft, exhibiting marine biofouling composed of marine green alga, on a non-biocidal abrasion-resistant coating (red shade). Photo by Dinis Reis Oliveira © 2019, Gothenburg.

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Abstract

Submerged surfaces at sea are colonized by a high diversity of sessile (i.e. attached) life forms. As the merchant fleet capacity increases, responding to growth in demand for seaborne transport, so does the hull wetted surface area that is prone to colonization by these sessile organisms, i.e. marine biofouling. Such colonization leads to increased ship hull surface roughness, which results in both environmental and economic issues, namely fuel penalties and increased emissions to air. Improved maintenance of the hull would not only reduce these penalties, but also reduce emission of antifoulants and other paint components to the marine environment, as well as risks related to the transport of non-indigenous species on fouled hulls.

The work presented in this thesis aimed at improving current approaches to the management of ship hull fouling, which typically rely on a combination of fouling-control coatings and an in-water cleaning scheme. Knowledge on the adhesive strength of fouling to minimize cleaning forces, on the one hand, and evaluation of the hull condition and hull roughness penalties, on the other hand, are therefore central to the aim of this thesis.

The outcome of performed work supports a **preventive** approach to hull maintenance, e.g. gentle and frequent cleanings (hull grooming), or an alternative **predictive** approach, based on vessel performance and condition monitoring for detecting early forms of fouling. Tools are provided with potential to improve hull maintenance practices. These include minimizing cleaning forces applied during in-water hull cleaning through knowledge on adhesion strength of fouling (**Papers I, III and IV**), and more-accurate determination of the impact of fouling on vessel performance, namely by accounting for hull form effects (**Papers II**) or using a novel performance indicator that would be applicable in wider comparisons between vessels (**Paper V**). Seen as a whole, results indicate that the goal of minimizing the environmental and economic risks involved in hull fouling management can only be achieved through continued collaboration between different industry stakeholders, researchers, technology developers, authorities and policymakers, leading to an optimal path in development.

Keywords: biofouling; fouling control coatings; adhesion strength; in-water hull cleaning; hull grooming; turbulent boundary layer; roughness; ship resistance; vessel performance.

Acknowledgements

In nature nothing exists alone.

Rachel Carson (*in* 'Silent Spring', 1962)

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Appended papers

This thesis is based on the following appended papers:

- I. Oliveira, D, Granhag, L (2016). Matching forces applied in underwater hull cleaning with adhesion strength of marine organisms. *Journal of Marine Science and Engineering* 4(4), 66–78.
- II. Oliveira, D, Larsson, AI and Granhag, L (2017). Effect of ship hull form on the resistance penalty from biofouling. *Biofouling* 34(3), 262-272.
- III. Oliveira, D, Larsson, L and Granhag, L (2019). Towards an absolute scale for adhesion strength of ship hull microfouling. *Biofouling* 35(2), 244-258.
- IV. Oliveira, D and Granhag, L (–). Ship hull in-water cleaning and its effects on fouling-control coatings. Manuscript submitted to *Biofouling*.
- V. Oliveira, D, Granhag, L and Larsson, L (–). A novel indicator for ship hull and propeller performance: examples from two shipping segments. Manuscript submitted to *Ocean Engineering*.

The author of this thesis contributed to the ideas presented in the above papers and had a major role in planning, data collection, data processing, preparation and running of experiments, as well as analysis of results and writing.

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Nomenclature

C	smooth wall intercept
C_T	total resistance coefficient, $C_T = R_T / (\frac{1}{2}\rho U_{STW}^2 S)$ [-]
ΔC_T	change in total resistance coefficient, $\Delta C_T = C_{T,rough} - C_{T,smooth}$ [-]
Fr	Froude number, $Fr = U_{STW} / \sqrt{gL_{WL}}$ [-]
k	arbitrary roughness height [m]
k_s	equivalent uniform sand roughness height [m]
k_t	peak-to-valley roughness height measured within a linear length of 50 mm [m]
K	form factor (ITTC-78) [-]
g	gravitational acceleration [m/s ²]
L_x	longitudinal distance from the bow [m]
L_{WL}	waterline length [m]
P	shaft power, $P = R_T U_{STW} / \eta_D$ [W]
ΔP	change in propulsive power due to hull roughness [W]
R_T	total towing resistance [N]
ΔR	change in resistance due to hull roughness [N]
Re	Reynolds number based on waterline length, $Re = L_{WL} U_{STW} / \nu$ [-]
Re_x	Reynolds number based on longitudinal distance from the bow and vessel speed through water, $Re_x = L_x U_{STW} / \nu$ [-]
S	wetted surface area [m ²]
U_{STW}	ship speed through water [m/s]
U_{SOG}	ship speed over ground [m/s]

u, v, w	time-averaged velocity components [m/s], corresponding to each of direction x, y, z
u_τ	friction velocity, $u_\tau = \sqrt{\tau_w/\rho}$ [m/s]
x, y, z	longitudinal tangential, normal and girth-wise tangential coordinates on the hull [m]
ε	wall origin error [m]
κ	von Kármán constant [–]
η_D	propulsive coefficient [–]
ρ	density of the fluid [kg/m ³]
ν	kinematic viscosity of the fluid [m ² /s]
τ_w	wall shear stress [N/m ²] = [Pa]

Superscript

+	inner-scaling of a variable, using u_τ for velocity scale, or ν/u_τ for length scale
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Abbreviations

AF	anti-fouling paint (containing biocides)
CDP	Controlled-Depletion Polymers
CFD	Computational Fluid Dynamics
EDX	Energy-Dispersive X-Ray analysis
EPS	Extracellular Polymeric Substances
FR	foul-release coating (biocide-free paint)
GT	Gross Tonnage, measure of overall enclosed volume of a ship
IMO	International Maritime Organization
MGPS	Marine Growth Prevention Systems
NIS	non-indigenous species

RANS	Reynolds Averaged Navier-Stokes
RoRo	Roll-on/Roll-off cargo ship
ROV	Remotely Operated Vehicle
SEM	Scanning Electron Microscopy
SP	Self-Polishing coating (organotin-free)
SPC	Self-Polishing Copolymer (containing organotin)
XRF	energy-dispersive X-Ray Fluorescence spectroscopy

1. Introduction

'Someone's got to do these things,' he said sullenly. 'Else Fate would not ever get nose-thumbed and mankind would still be clinging to the top branches of a tree.'

John Steinbeck (*in* 'East of Eden', 1952)

The year was 2019. Humanity had reached a new high in its development, with a record life expectancy of ~70/75 years (male/female, world average), compared to ~64/68 years just two decades earlier (UN, 2019). However, such continued improvement in quality of life was not without its challenges.

The previous year had seen renewed alerts from the scientific community regarding environmental impacts, namely the consequences of climate change and the need for strengthening action (Allen *et al.*, 2018). In spite of a two-digit annual growth in energy sourced from solar and wind, our dependency on fossil energy (coal, gas and oil) was in 2017 still as high as ~81% of global energy supply, comparable with ~80% in year 2000 (IEA, 2019). Therefore, one may say that the situation had not fundamentally changed. To complicate matters, looming isolationist measures (e.g. Brexit), raising nationalisms, trade tensions between major economies, and economic sanctions, all contributed to high geopolitical uncertainty in entering year 2019 (BRS, 2019).

Within this context and constraints, the global shipping industry continued answering an ever-increasing demand for transport, in excess of some yearly 60 trillion ton-miles (¹), which is practically double the demand of two decades earlier (UNCTAD, 2018). Fuelled by low-priced bunkers, at about 0.3 to 0.5 USD / kg for heavy fuel oil, shipping is currently responsible for ~13% of total sulphur emissions, and 2-3% of greenhouse gas emissions to the atmosphere (IMO, 2014; Sofiev *et al.*, 2018). The latter emissions could well reach 17% of global carbon emissions by 2050, in a business-as-usual scenario (Halim *et al.*, 2018).

¹ Ton-mile is a unit of transport work, corresponding to 1 ton of cargo (1,000 kg) transported over 1 nautical mile (1,852 m).

Scrutiny on environmental impacts from a growing shipping industry followed at its own pace, with several regulatory initiatives from the International Maritime Organization (IMO) on different impacts from shipping, some of which are summarized here. Year 2019 was the last year for unhindered use of high-sulphur ship bunkers (3.5% m/m sulphur content) outside Sulphur Emission Control Areas (SECA). This sulphur cap leaves shipowners with the options of either switching to more expensive low-sulphur fuel alternatives (0.5% m/m) or investing in scrubbers for cleaning exhaust gases, the latter potentially shifting impacts from the atmosphere to the marine environment (Ytreberg *et al.*, 2019). Also, implementation of IMO's ballast water requirements for avoiding the spread of non-indigenous species (NIS), which had entered into force in 2017, continued in its experience-building phase. Finally, in 2019 the IMO set levels of ambition for cutting carbon emissions by 50% in 2050 compared to 2008 emissions, as well as reducing carbon intensity by 40% in 2030, which have yet to be matched with concrete and enforceable measures that would enable reaching such targets (MEPC, 2019). All these initiatives converge at a time of overcapacity (or risk thereof) in some shipping segments, especially for containerships and chemical tankers, and potentially in the Roll-on/Roll-off segment (RoRo) in the near future (BRS, 2019), which may lead to a relatively slow renewal of the fleet and correspondingly slow uptake of any new technologies. The latter uptake is critical in moving towards a more energy-efficient and low-carbon fleet (Halim *et al.*, 2018).

1.1. Motivation

Meanwhile, somewhere on the globe, a large commercial ship is going through her *roughest hour*. After having been idle for a prolonged period of 1-2 months, the ship's master reported to the technical management a noticeable loss in vessel speed. Upon lowering a water-tight camera overboard, the engine crew was able to identify the cause of such low performance: heavy marine growth, including exuberant filamentous alga on the sides near the waterline, and large barnacle shells growing further below on the ship's flat bottom. Such marine growth created millimeter-, nay, centimeter-scale roughness, thus increasing the hydrodynamic resistance of the travelling hull. The commercial management of that pool of vessels, consisting of about 50 ships in total, was thus contacted with a request for carrying out in-water hull cleaning. The request could not be accommodated by the pool, due to route and scheduling reasons. As a consequence, the charterer's bunker bill shall suffer an increase due to higher

fuel consumption, not to mention increased emissions to the atmosphere per ton-mile of transport work, and potential spread of NIS that may be travelling on the hull.

How was it possible for a modern hull to get to this point, after centuries of experience and research on preventing marine growth?

This thesis will address the specific issue of ship hull fouling management, as a way of reducing fuel consumption and emissions from shipping, while avoiding the trap of shifting impacts to other parts of the environment and society.

1.2. Background

The marine environment is especially rich in biodiversity in shallow waters close to coast lines. As soon as life forms find their way to a submerged solid surface and are able to adhere and colonize it, they give rise to biofouling. On manmade structures, this process is mostly deleterious, unless it provides a barrier against other types of deterioration, e.g. by forming a barrier against wood borers (Woods Hole Oceanographic Institute, 1952, p. 19).

On boats and ships, the biofouling issue has been a long-standing one. Already Plutarch, born circa AD 46, recognized the connection between marine growth and a ship's speed and manoeuvrability, as 'when weeds, ooze, and filth stick upon its sides, the stroke of the ship is more obtuse and weak' (Plutarch, no date). Today, commercial vessels visit a dry dock for inspection and repairs at least every five years (Takata, Falkner and Gilmore, 2006), though even higher docking intervals of 7.5 years might soon become possible, at least for some vessel classes (Bebić *et al.*, 2018). Within this dry-docking interval, hulls require some form of surface protection, combined with in-water maintenance, to keep the hull as clean and smooth as possible. The consequences of not doing so include increased hydrodynamic resistance, due to roughness effects on the water flow around the hull, as well as propulsive losses due to propeller blade roughness (Townsin, 2003). Besides these, loss of mechanical function and damage to anti-corrosive coatings should also be mentioned (Woods Hole Oceanographic Institute, 1952). Finally, a fouled ship represents a biosecurity risk, acting as a potential vector for spread of NIS, which may significantly disturb the receiving ecosystem (Drake and Lodge, 2007).

In the days of the Greek-Roman Plutarch, ships were already being sheathed with lead, which was fastened with copper nails and probably mitigate the

damages from wood borers, i.e. shipworm (Yebra, Kiil and Dam-Johansen, 2004). Only later in history, more precisely in the eighteenth century, did copper sheathing of wooden vessels take predominance in ‘preserving it against the Worm, [...] Weeds, or any other Cause’ (Woods Hole Oceanographic Institute, 1952). However, it was not until the nineteenth century that the antifouling effect of dissolved copper was demonstrated by Sir Humphrey Davy (Yebra, Kiil and Dam-Johansen, 2004). Copper compounds are still widely used in today’s anti-fouling coatings, as further detailed in chapter 2.

‘There you have it’, someone may say, ‘simply load the hull with enough biocides, making sure to cover the whole spectrum of possible biofoulers, and that’s it, problem solved!’ Well, those biocides and other active compounds may still have effects on non-target organisms, as the infamous organotin compounds, which were banned by the IMO from further application, beginning in 2003 (IMO, 2001). Additionally, biofouling populations that become tolerant to a biocide may still dodge our best efforts to prevent fouling with a biocidal coating (Piola, Dafforn and Johnston, 2009; McKenzie, Brooks and Johnston, 2011), not to mention the many ways in which such coatings may fail, due to formulation or application defects (Weinell and Yebra, 2009). Even biocide-free coatings are not without their own disadvantages, as further explored in chapter 2.

Where protective methods, such as sheathing or coatings, fail to prevent marine fouling within the dry-docking interval, active maintenance is required to avoid significant propulsion penalties. Sail ships used to be ‘careened’, which involved scraping with ‘sharp brushes’ and ‘irons that are crooked for the purpose’ (Woods Hole Oceanographic Institute, 1952). Today, in-water cleaning is performed by divers, using underwater cleaning carts, or Remotely Operated Vehicles (ROVs) of various configurations, relying on rotating brushes, waterjets or contactless methods (Morrisey and Woods, 2015). An important requirement for such devices is to effectively capture biological waste or render it non-viable, as to minimize the risk of transfer of NIS. Additionally, collecting any paint debris and minimizing the release of biocides during cleaning should be considered (IMO, 2011). Avoiding paint/biocide release peaks is also in shipowners’ interest, considering that a depleted or otherwise damaged coating will foul more rapidly in the period subsequent to the cleaning, leading to faster deterioration in vessel fuel performance (Malone, 1980; Munk, Kane and Yebra, 2009).

1.3. Current aim, research questions and research methodology

Before leaving anchorage and delving further into the topic of biofouling and its mitigation, some bearings and intentions need to be stated.

The current research aim is to **provide tools for future improvement in hull maintenance practices**. The topic of ‘maintenance’ encompasses all forms of intervention required to keep the hull as smooth as possible, including activities such as hull surface preparation in the dry dock, hull coating application, and in-water hull cleaning. All these activities are interrelated, as coating selection affects the future need for in-water cleaning, which in turn may affect subsequent dry-docking activities (Schultz *et al.*, 2011; Pagoropoulos *et al.*, 2017).

Within this general frame, Figure 1 illustrates the overview of research areas under investigation, as well as the connectivity to and between papers appended in this thesis. With the general aim of improving practices in hull maintenance, this thesis focuses on developing methods for determining, on the one hand,

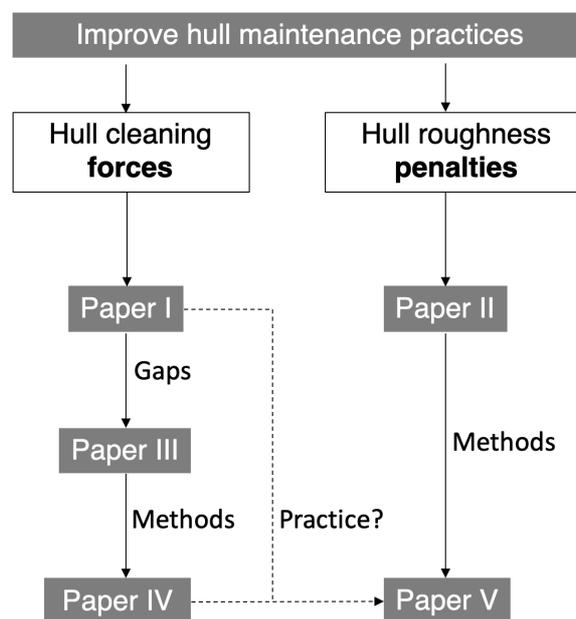


Figure 1 – Overarching research areas and connectivity between appended papers.

in-water hull cleaning forces required for removing marine growth, and on the other hand, more accurately determining the impact of any type of maintenance on **hull roughness penalties**. The relevance of these research areas to the aim of this thesis will become clearer by specifying research questions, as well as their respective appended papers, as detailed next.

As mentioned in section 1.2 Background, a coated ship hull may lose its protection against fouling, due to either coating depletion or some form of coating failure, thus requiring in-water cleaning to avoid further roughness-related fuel penalties and emissions to the atmosphere. The following main research questions are thus posed (associated papers indicated between brackets):

- 1) What level of in-water cleaning forces is required to remove marine growth? (Papers I and IV)
- 2) How are required forces related to the timing of the cleaning? (Paper I)
- 3) How to determine cleaning forces on an absolute scale? (Paper III)
- 4) What are the effects of minimal cleaning forces on hull coatings, including coating deterioration and biocide emissions to water? (Paper IV)
- 5) How to quantify the impact of maintenance on ship resistance and powering? (Papers II and V)

Paper I, a review of previous literature on adhesion strength of marine biofouling from lab-scale experiments, pointed to knowledge gaps that hinder from matching in-water cleaning forces to those minimal forces required for fouling-substrate adhesion failure (question 1). Further, Paper I collected data available from the literature on the evolution in adhesion strength with time (question 2), by reviewing the consequences of allowing marine growth to develop into advanced stages.

Knowledge gaps identified by Paper I led to a numerical study on waterjet testing of adhesion strength, Paper III, which provided semi-empirical formulas for quantifying cleaning forces (question 3). These semi-empirical formulas were then applied in field-testing of coatings in Paper IV. In the latter paper, effects of quantified cleaning forces on coatings were further investigated (question 4). These effects included coating damage evaluated from visual inspection, paint wear from thickness measurements, and condition of the top layer of coating from cross-section microscopy-imaging of coating samples. Finally, the latter wear and top-layer condition enabled to estimate emissions of biocides to water (Paper IV).

Since one of the main reasons for hull maintenance is to save bunker fuel used for propulsion and to reduce emissions to air, maintenance of the hull must be also assessed in terms of avoided resistance and powering penalties. Two complementary approaches are followed in order to answer question 5, which deals with quantifying the impact of maintenance on ship resistance and powering: on the one hand, by attempting to improve methods for translating a certain observed hull condition (e.g. from diver reports) into a hydrodynamic resistance penalty (Paper II); on the other hand, by making use of onboard vessel performance data (i.e. propulsion power, speed, and other operational and environmental variables) to evaluate the hull/propeller condition, not only for a vessel compared to itself, but also for comparing hull/propeller performance among different vessels and operating conditions (Paper V). The later paper proposes an iterative procedure, based on methods discussed in Paper II, for estimating hull roughness from onboard collected data. Both condition-to-penalty and penalty-to-condition approaches are discussed in terms of their advantages and caveats in regard to evaluating the effectiveness of hull maintenance approaches. Additionally, this thesis reveals a gap between recommendations on in-water maintenance, as given in Papers I and IV, and current practices in the merchant fleet, as observed in Paper V (dashed line in Figure 1).

1.4. Scope and delimitations

What are the boundaries of the current thesis? What is left outside its scope? These reflections are summarized in the current sub-section. For methodological questions, the reader is referred to sub-section 4.5 Methodology.

The topic of this thesis indirectly touches upon broader issues, such as chemical pollution of the marine environment, biosecurity risks, air pollution, and anthropogenic climate change. However, it is not within its scope to provide a detailed analysis on these topics, even less provide prescriptions for these complex issues, as summarily reflected upon in sub-section 1.5.

The current discussion focuses on large commercial ships, i.e. cargo ships of at least 300 GT (Gross Tonnage) and passenger ships of at least 100 GT, as opposed to smaller crafts, such as recreational boats. Further, it focuses on internationally-trading vessels, which share a common regulatory background, being subject to IMO conventions, class rules from classification societies, port state controls, among other national or regional regulations (Stopford, 2009). International vessels account for more than 80% of CO₂ emissions from shipping

(IMO, 2014) and represent higher risk in terms of transport of non-indigenous species (Morrisey *et al.*, 2013).

Looking more closely at the biofouling issue, this thesis does not deal directly with coating development, and it navigates within the current coating market situation, where copper-based biocidal paints still dominate and non-biocidal coatings correspond to a minor share of probably less than 10% (Lindholdt *et al.*, 2015). Also, a life-cycle assessment of different coatings is not attempted, which would need to consider both upstream and downstream emissions, e.g. from paint manufacturing to paint waste processing. Such an approach would also include details on energy sources (Bergman and Ziegler, 2018).

Further, tools in vessel performance are demonstrated for two vessel types, with available data for only three individual vessels (Paper V). Therefore, results cannot be interpreted as representative of the entire commercial fleet, though the methods are, themselves, more widely applicable (Paper II and V). Also, it is not the current aim to look into detailed economic analysis of hull maintenance practices. Such analysis will require full consideration of a range of economic factors, such maintenance costs, bunker fuel price and its volatility, vessel activity, specific chartering conditions, and constraints due to trade routes (Stopford, 2009; Pagoropoulos *et al.*, 2017).

Current field results presented in Paper IV are obtained for the biofouling community near the Port of Gothenburg, Sweden (Kattegat Sea), and it is recognized that adhesion properties of fouling may differ from those in other sites around the world, with different biotic and abiotic conditions. Also, dynamic immersion of coated surfaces was not currently included, which would likely influence the amount, diversity and properties of fouling, by subjecting samples to hydrodynamic stress (Zargiel and Swain, 2014). Dynamic testing requires a definition of vessel activity, which is not a trivial decision considering widely-varying operational profiles across the world's fleet: e.g. 12-15 knots (²) for tankers, compared to 14-25 knots for containerships (Stopford, 2009, pp. 584, 596), as well as varying hydrodynamic conditions across different areas on a given hull (Schultz *et al.*, 2003). Nevertheless, currently developed tools may still be useful in future testing on dynamically-exposed coatings.

Finally, cleaning forces exerted by specific commercial cleaning devices are not currently investigated, though methods are discussed on how to achieve this

² Conversion to SI units: 1 knot \cong 0.5144 m/s.

(Paper III and IV). Also, the cleaning and waste-capturing efficacy of such devices are not presently evaluated.

1.5. Ethics, sustainable development, and end use

It is one of researchers' tasks to continually reflect upon ethical issues, impact on sustainable development, and end use of research, in an attempt to identify and recommend mitigation of future unintended consequences of research. The current sub-section summarizes some of the points related to these reflections.

All research requires funding, and might also require access to third-party data and materials. The source of funding and the conditions for accessing data or materials should be such that no obstacles or commercial bias lay in the way of the researcher's inquiry.

Regarding research funding, the current work was entirely funded by the public sector, initially by the Swedish Energy Agency, and more recently by the European Regional Development Fund. This means that no private/commercial interests are directly involved, and that results are made available to the general public through Open Access publishing, potentially reaching a wider audience.

Regarding access to data and materials, vessel performance data was made freely available by two collaborating shipping companies, and some of the deployed panels coated with fouling-control product were prepared and provided also free-of-charge by the paint manufacturer. Nevertheless, the researchers' freedom of inquiry and publishing was guaranteed, with design and running of experiments, as well as analysis and interpretation of results, being the sole responsibility of researchers employed by public projects. The only condition was that of confidentiality regarding names of shipping companies and vessels, achieved by anonymizing vessels and omitting fields related to vessel position and timestamp. The fulfilment of confidentiality was checked by representatives from each shipping company, with no damage to any of the research findings.

Further into the impact of research, one should ask what might be the consequences of current research for stakeholders and, in broader terms, for sustainable development? Listing and analysis of potential consequences for stakeholders, as well as a qualitative assessment of potential implications for sustainable development, is next discussed. The latter discussion on sustainable development will use the Five Capitals framework (Stacey and Stacey, 2012).

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The main stakeholders are currently identified as: shipowners (or more generally, shipping companies), charterers, cargo owners, other transport modes, bunker suppliers (or more generally, energy suppliers), developers of hull cleaning devices, commercial diving companies, paint manufacturers, shipyards, funders, environmental agencies and regulatory bodies.

By delivering tools that help better maintain and evaluate the condition of a ship hull, shipping companies may be able to improve their operational results, through lower energy consumption, as well as minimized maintenance costs related to the hull. This is of additional importance in some charter contracts (charter parties) wherein the shipowner is financially responsible for maintenance of the vessel, and the charterer (and ultimately the cargo owner) is charged with energy costs, potentially leading to split incentives (Johnson, 2016). In this context, the tools provided in the current work have the potential to provide increased transparency, as knowledge and tools are made available to all parts.

In case of direct competition with other transport modes, as well as local primary and transformative industries, these may suffer from an increased competitiveness of shipping, gained through increased energy efficiency. In other cases, since shipping is only one part of the supply chain, the whole transport logistics may benefit from a more efficient and predictable transport by sea.

Bunker or energy suppliers would in principle be negatively affected by a more efficient shipping sector, which would reduce their revenue (bunker sales), though it is questionable whether this factor would be of significance in a scenario of increasing demand for transport and considerable volatility in bunker prices.

Developers of hull cleaning devices, diving companies and paint manufacturers might benefit from open data on the continued effects of cleaning forces on main coating types used today, as well as an indication on the absolute forces required for cleaning those coatings. More specifically, paint manufacturers would benefit from, or else be negatively impacted by, third-party demonstration of performance of their products, or lack thereof. However, even in case of coating failure being detected, this would still serve as a learning opportunity for paint manufacturers, and researchers should strive for clearly identifying any possible causes of coating failure.

Shipyards would reduce the turnaround time in dry-docking repairs, by shortening the average time for hull surface maintenance. Shipyards would also cut the costs related to environmental management of paint waste (Schulz and

Pastuch, 2003), since less removal by sand/hydro-blasting of damaged hull coating systems would be required, and resources could thus be dedicated to other issues.

Public funding bodies are expected to represent the interests of society. It follows that if research fails to provide outcomes that are aligned with the direction set as a priority by society, i.e. contributing to its core values, investment has not succeeded in its purpose, and resources were wasted which could have been applied in other areas. Thus, even though the allocation of resources is in the hands of funding bodies, the researcher should strive towards clarifying his/her role and communicating effectively the intended outcome and its precise implications, as well as limitations. In utilization of outcomes of current research, caution should be exercised by governmental bodies in striking a balance between a too-hasty implementation of some solutions to the problems at hand, e.g. by issuing approvals for in-water ship hull maintenance in the absence of solid evidence of the risks involved (if any), *versus* strict prohibitions that do not incentivize further technology development and instead promote outsourcing of environmental and societal issues to other geographical areas (Scianni and Georgiades, 2019). Finally, researchers working with incremental approaches should openly admit to this, as is done here. Focusing exclusively on incremental change comes with the danger of locking society into a certain developmental paradigm. Instead, when faced with major societal challenges, such as chemical pollution, air pollution, and anthropogenic climate change, second-order change may be required, transcending today's ways of thinking and acting, towards 'previously unimagined possibilities' (Fazey *et al.*, 2018).

These reflections lead us to a discussion on sustainable development, which is now analysed through the optics of the Five Capitals framework (see Stacey and Stacey, 2012): the Natural, Human, Social, Manufactured and Financial capitals.

By potentially contributing to an increase in ship hull performance, the current work might contribute to reduce the burden on the Natural capital through helping shipping towards mitigating its carbon intensity, i.e. reducing its emissions per unit of transport work. However, there is a possibility that focusing exclusively on performance may be counter-productive: by reducing its carbon intensity, the shipping industry may be justified to expand, potentially coming to a situation where it might be difficult, if not impossible, to fulfil global emission goals. Thus, for instance, it is possible that even if the IMO's 40% reduction target in carbon

intensity is achieved by 2030, global emissions from shipping might still continue to rise, instead of halving by 2050, due to increasing derived-demand for transport and a too slow transition to alternative energy sources. This trend would further be promoted by what is commonly known as the Jevons' paradox, by which any improvement in terms of resource efficiency may ultimately result in an increase in demand and global consumption of that resource (Freire-González and Puig-Ventosa, 2015). Thus, an emission-increase scenario by 2050 is not unlikely, judging from the latest IMO projections (IMO, 2014). One can only press for that, sooner than later, effective measures be agreed upon at the IMO level to quickly reverse the business-as-usual trends in shipping emissions. Additionally, shipping transports about 90% of global trade (ICS, 2017), so the complex interplay with other emitting industries that depend on sea transport should be further considered, as an increasingly-efficient sea transportation may foster unsustainable growth in other sectors.

Improved management of hull surfaces would certainly contribute to reducing the biosecurity risk of introduction and spread of NIS, thus maintaining the Natural capital, i.e. assets such as biodiversity. However, misuse of the outcomes, e.g. without taking into full consideration complete removal and proper capture and treatment of biological waste during and after in-water cleaning, may lead to increased risks. Biosecurity risks, as well as chemical pollution from antifoulants, should be minimized through effective regulations on in-water hull cleaning, following evidence-based guidelines (Morrisey *et al.*, 2013; Scianni and Georgiades, 2019).

By reducing the intensity of global shipping emissions, Human capital would benefit through avoided impacts on human health. Currently, ~250,000 yearly premature adult deaths are attributed to shipping emissions, even after implementation of the IMO's 2020 sulphur cap (Sofiev *et al.*, 2018). Thus, a higher performance would contribute to lowering emissions per transport work, and a correspondingly lower number of premature deaths for that same transport work. Additionally, the risk of spread of diseases and parasites via ship hulls should be considered (Champ, 2000), and their release during vessel stays and in-water cleaning events should be targeted by effective and enforceable in-water cleaning regulations, as to not impact the Human and Natural capitals.

To the best available knowledge, there are no precise figures on the share of in-water hull-cleanings that is performed by divers, though these are assumed to be far more common than ROV in-water cleanings. Also, to the best available

knowledge, there are currently no ROV/autonomous systems available for reaching niche areas, which are routinely cleaned by divers (e.g. propeller polishing). This situation may pose an increasing risk for fatal accidents with divers in case of increasing frequency of proactive cleanings. Thus, unless ROV and autonomous systems continue to expand, some Social capital may be at risk. Additionally, the livelihood of coastal communities might be threatened by some in-water hull cleaning practices, through negative impacts of NIS and chemical pollution on coastal ecosystems, on which local economies depend.

Manufactured capital, which includes all material goods that are not embodied in a final output, would benefit from a push towards increasingly advanced devices for hull maintenance, as well as ship sensors and algorithms for analysing vessel performance. Such improved systems would also lead to changes in the working environment for bridge officers, marine engineers, shore personnel and professional divers, towards increased occupational safety (e.g. ROVs instead of divers for in-water hull cleaning) and increased automation of some tasks, which should be replaced by more rewarding collaborative ones, thus increasing the Social capital.

Regarding the Financial capital, a more efficient management of the hull condition would lead to a positive economic result, contributing to the cost-effectiveness of sea transport. These savings would mean possible re-investment in other areas of shipbuilding, operations and repair, namely through enabling more detailed and transparent chartering clauses between shipowners and charterers (BIMCO, 2013; Rehmatulla and Smith, 2015).

1.6. Navigating this thesis

This thesis is based on five appended papers, which will be further introduced and discussed in the following chapters.

In chapter 2, the general reader not acquainted with marine fouling will hopefully find some guidance on different types of ship fouling and methods currently used in either preventing or removing it from ship underwater surfaces.

In chapter 3, fundamentals are reviewed regarding the impact of biofouling and hull roughness on ship hydrodynamic resistance.

ROUGHEST HOUR

In chapter 4, outcomes from appended papers and methodological aspects are discussed, with an outlook on future research and development.

Everything must come to an end, and this thesis concludes with highlighting of the main contributions and learnings from the current work.

2. The enemy below

As, at last, the boat was hooked from the bow along toward the gangway amidship, its keel, while yet some inches separated from the hull, harshly grated as on a sunken coral reef. It proved a huge bunch of conglobated barnacles adhering below the water to the side like a wen—a token of baffling airs and long calms passed somewhere in those seas.

Herman Melville (*in* 'Benito Cereno', 1856)

An idling ship, as in the 'long calms' of Melville's age of sailing, is an easy target to marine organisms with a natural taste for a 'sedentary' way of life, i.e. sessile (attached) stages of life, which constitute biofouling. Indeed, any unprotected manmade object deployed at sea will develop some form of biofouling, eventually of such complexity that has been paralleled with that of our own cities (Kolter and Watnick Paula, 2000).

This chapter attempts a brief description of marine biofouling, as well as methods commonly used in preventing ship hull fouling. Regarding the latter methods, one should always be humbled by the fact that marine biofouling existed, in forms closely related to those of today, several geological epochs (tens of millions of years) before the very first manmade structures at sea (Harzhauser *et al.*, 2019). Lest our own methods against biofouling become the 'enemy below', undermining ecosystem services upon which humans and numerous other species depend upon for survival.

2.1. A description

Marine fouling ranges from the adhesion of organic molecules and particles, to organisms of increasing complexity: bacteria, diatoms (single-celled algae), protozoa, spores of macroalgae, attached larvae, and finally the adult stages of macroalga and animal fouling. According to the size of individuals or colonies, biofoulers are classified into micro- or macrofouling (Dürr and Thomason, 2009). In practical approaches to rating of fouling, a distinction is also made between

types of fouling with and without a visible calcareous shell, i.e. soft and hard fouling, respectively (Naval Sea Systems Command, 2006).

Some examples of biofouling are given in Figure 2, ranging from microfouling, a.k.a. marine biofilms or slime (Figure 2a), to macrofouling (Figure 2b-d). The latter macrofouling can be either soft, in the case of macroalgae (Figure 2b) and tunicates (not shown), or hard fouling, in the case of encrusting bryozoans and barnacles (Figure 2c-d), and mussels (not shown). The current list of known marine biofouling species contains in excess of 4,000 species, though an

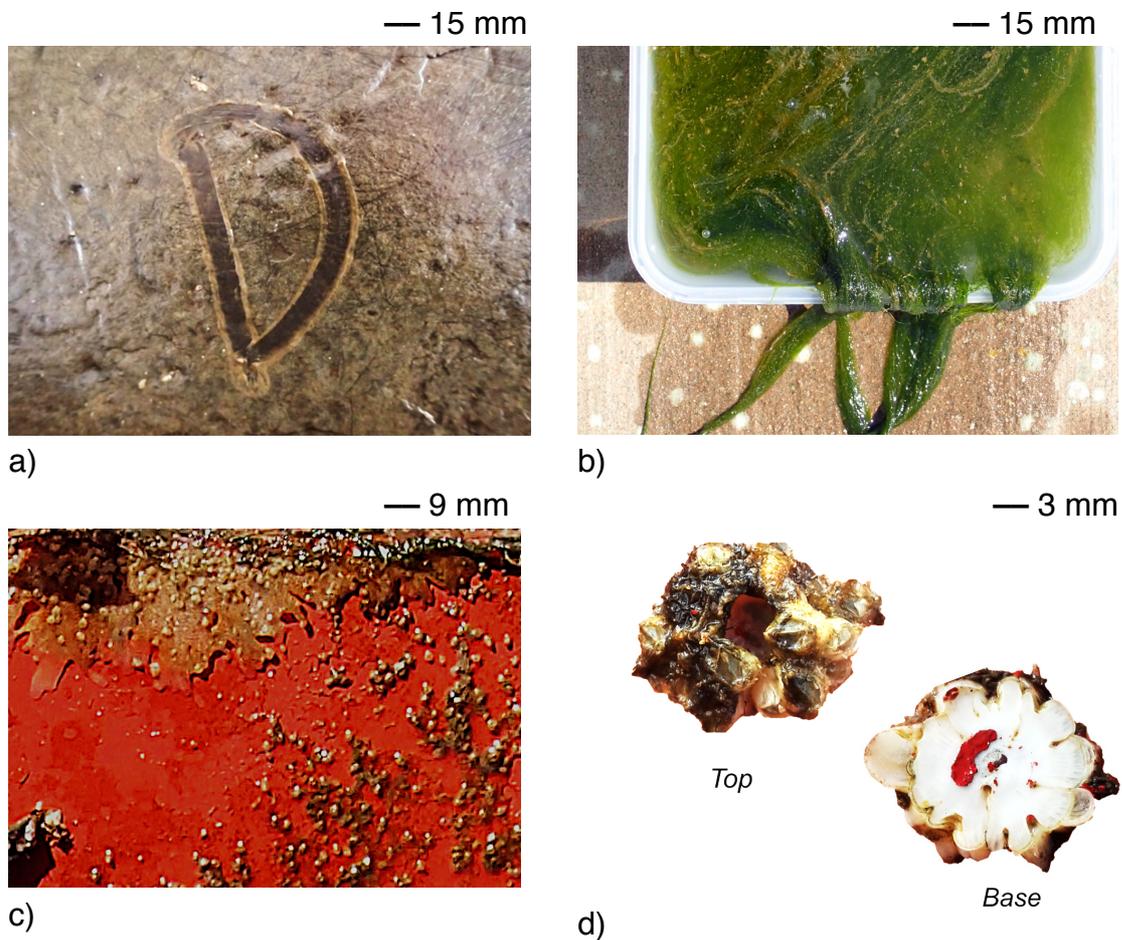


Figure 2 – Common examples of biofouling found on manmade structures around Gothenburg, Sweden: a) microfouling, or slime, developed on a decommissioned mine layer; b) macroalgae *Ulva* sp., grown on unprotected anti-corrosive coating; c) encrusting bryozoans (upper left corner) and barnacles (lower right corner) on a non-biocidal silicone coating; d) top- and base-view of barnacles removed from an old biocidal copper coating (red debris). Image source: author's own archive.

admittedly lower number is able to resist fluctuating environmental conditions on ship hulls (Yebra, Kiil and Dam-Johansen, 2004). Besides propagule availability in the water, the most important environmental factors that determine fouling assemblies correspond to light, temperature, salinity, pollution and hydrodynamic stress (Woods Hole Oceanographic Institute, 1952, pp. 102–107). These factors fluctuate on an active hull, and also vary according to zones on the hull, leading to spatial heterogeneity of hull fouling (Schultz, 2007; Swain and Lund, 2016).

2.2. Choose your weapons

Depending on vessel characteristics, there are different options for preventing hull fouling. In this sub-section, both passive and active methods are reviewed, along with their advantages and disadvantages.

The difference between passive and active methods resides in the former requiring no direct energy input. Passive methods commonly consist in applying a fouling-control coating while in dry dock. At some point, a steel hull will be fully sand/hydro-blasted to remove old layers of paint, and a complete system consisting of layers of anti-corrosive primer, followed by a tie-coat for coating adhesion, and a final top layer (or layers) of a fouling-control coating. In some cases, only localized touch-up to the uppermost layers is required during repairs (Townsin *et al.*, 1980; Weinell and Yebra, 2009).

Commercially available fouling-control coatings are grouped into two main categories, according to their prevention mechanism. Anti-fouling coatings (AF) prevent fouling through controlled release of active substances to sea water, in most cases biocides. The second type, foul-release coatings (FR), exhibit non-stick surface properties that lead to reduced adhesion between biofoulers and the surface of the coating, enabling sloughing biofouling off by travelling at a given speed (Yebra, Kiil and Dam-Johansen, 2004). Additionally, hybrid coatings have been also proposed, which combine foul-release properties with a low concentration of biocides (e.g. Radenovic *et al.*, 2014).

Today's AF coatings are the successors in a legacy of historical methods, which in the 1800s released substances such as copper oxide, mercury oxide and arsenic into the marine environment (Yebra, Kiil and Dam-Johansen, 2004). More recently, in the second half of the twentieth century, self-polishing organotin coatings boomed, only to be proven harmful to non-target species, and finally banned in the turn of the century (IMO, 2001). In spite of this ban, the persistence

of organotin compounds in old layers of paint, as well as in sediments, stands as a warning for the risks involved in approval of new biocides (Lagerström, 2019). Currently, the most common biocides include metallic compounds, such as copper and zinc compounds, which are typically complemented with so-called booster biocides, such as zinc pyrithione and zineb, for wide-spectrum action (Yebra, Kiil and Dam-Johansen, 2004). Finally, other active substances have reached commercial maturity, relying on mechanisms other than toxicity to prevent fouling, e.g. reversible anti-settling effects on larva (Holm, 2012).

AF coatings are typically grouped into three main types, according to the release method for active substances, and the type of binder. Even though this grouping certainly oversimplifies the almost continuum myriad of available paint formulations, these illustrate the most common anti-fouling mechanisms (Yebra, Kiil and Dam-Johansen, 2004; Lindholdt *et al.*, 2015):

- **Insoluble matrix paints** – embedded biocides are gradually dissolved in seawater, leaving behind a porous layer of inert polymeric matrix. As the biocide is depleted from upper layers, diffusion from increasingly deeper layers of coating leads to a rapidly-decaying biocide release rate and early failure, i.e. fouling. Mainly due to this disadvantage, these coatings correspond today to a limited share of the market.
- **Soluble matrix paints** – replacing inert polymeric materials by soluble rosin-based matrixes mitigates the above diffusion issues. Still, unless the vessel is active, a biocide-depleted layer develops, which is also known as ‘leached layer’. Modern versions of these coatings, so-called Controlled-Depletion Polymers (CDP), led to a higher predictability of the ablative process by incorporating reinforcing polymers, which also improved the mechanical properties of these paints.
- **Self-Polishing (SP) coatings**– these coatings are claimed to mimic the mechanism of banned organotin paints, through alkaline hydrolysis of the matrix in contact with sea water. Some of the advantages include a progressively smoother surface finish throughout the lifetime of the coating, and a leached layer with stable thickness, resulting in a more stable release rate. In practice, it is not always clear from the information provided in product datasheets whether a given commercial AF product acts as an SP or as a soluble CDP coating.

Even though biocidal coatings still dominate today's market for ship hull coatings (Lindholdt *et al.*, 2015), previous bans on harmful active substances – first at a national, and later at international level – promoted the development of alternatives, most notably foul-release (FR) coatings (Lejars, Margailan and Bressy, 2012). These FR coatings exhibit physical or surface chemistry properties that reduce the strength of the bioadhesive-surface joint, i.e. the fouling-coating interface, therefore releasing fouling more easily under shear. Finally, other types of non-biocidal fouling-control coatings are now in the market, such as self-polishing biocide-free coatings. However, experience on the long-term performance of these coatings on large commercial vessels is comparatively limited (DRYDOCK Magazine, 2019).

Two main types of FR coatings exist, namely silicone-elastomer and fluoropolymer coatings, which differ in terms of composition and mechanical properties (Yebra, Kiil and Dam-Johansen, 2004). Foul-release properties of silicone-elastomer coatings are further improved by adding unbound silicone oils to the formulation, which accumulate at the surface and eventually exude into the environment (Watermann *et al.*, 2005). Even though these oils have low toxicity towards aquatic organisms, their low biodegradability and accumulation in the environment calls for further investigation, especially regarding possible physical–mechanic effects on organisms and sediment habitats (Nendza, 2007). Additionally, that a coating is biocide-free does not necessarily imply no hazard to the environment, as leaching of other ingredients from the paint, e.g. plasticizers and catalysts, may also be cause for concern (Watermann *et al.*, 2005; Ytreberg, Karlsson and Eklund, 2010; Piazza *et al.*, 2018).

Besides the main environmental benefit of avoiding release of biocides to the marine environment, silicone-based FR coatings may also enable low-friction out-of-dock roughness profiles to be achieved, resulting in lower frictional drag compared to newly-applied conventional AF paints (Candries *et al.*, 2003). However, paint application costs are probably still higher for FR products compared to AF paints (Yebra, Kiil and Dam-Johansen, 2004; Lindholdt *et al.*, 2015). There is also a risk of silicone contamination of spray equipment, which needs to be thoroughly cleansed before working with other coating products. For the same reason, silicone should not be allowed to reach other areas of the ship, typically requiring the use of canvasses for protection of areas that are not being painted (Yebra, Kiil and Dam-Johansen, 2004; Blanco-Davis, del Castillo and Zhou, 2014). Finally, some performance drawbacks have been described in the literature, including: low mechanical properties and thus some sensitiveness to

impact damage, especially on highly-curved surfaces such as weld beads (Yebra, Kiil and Dam-Johansen, 2004; Hearin *et al.*, 2015); failure to prevent macrofouling at too low vessel speed and towards the aft of the ship, i.e. at lower hydrodynamic shear stress (Schultz, Kavanagh and Swain, 1999; Yebra, Kiil and Dam-Johansen, 2004); and an often-described selection for strongly-attached tenacious biofilms under shear resulting from vessel movements, which cannot be removed by gentle cleaning (Holland *et al.*, 2004; Hearin *et al.*, 2016). Finally, at least some of these coatings exude silicone oils, as in the case of the foul-release product in Paper IV. These oils contribute to the initial efficacy of these coatings, but as the surface oil gets depleted, the coating may lose its effectiveness (Yebra, Kiil and Dam-Johansen, 2004). Also, the exuding of such silicone oils deserves further scrutiny (Nendza, 2007), since physical-mechanical effects have been observed on barnacle larva (Watermann *et al.*, 1997).

From the above, it becomes clear that, under certain conditions, passive methods may eventually fail to prevent fouling, as a coating may get depleted or damaged in some way or another. Active methods are therefore required for removing fouling that is causing unacceptable propulsion penalties, or simply as a proactive approach to hull maintenance, especially in the case of coatings that offer no protection against fouling (Rompay, 2013). These methods include **in-water hull cleaning**, used as a *reactive* approach in face of a certain level of fouling or propulsion penalty, and **in-water hull grooming**, suggested as a *proactive* approach consisting in gentle and frequent cleaning events (Tribou and Swain, 2015). Although both cleaning and grooming can in principle be performed by either divers or ROV cleaning devices, hull grooming is best suited for ROV or autonomous devices, given its weekly or even higher frequency. Regarding reactive in-water hull cleaning, there is a comparatively higher risk of damage to fouling-control coatings (Tribou and Swain, 2017), which may lead to a faster development of fouling after cleaning (Malone, 1980; Munk, Kane and Yebra, 2009).

Besides cleaning and grooming, other active methods have been proven to be effective to a certain degree, including prevention of fouling using ultrasound transducers (Park and Lee, 2017), aeration (Menesses *et al.*, 2017) and heat treatment (Inglis, Floerl and Woods, 2012; Cahill *et al.*, 2019). However, these technologies are so far only attractive for boats or niche areas on larger vessels, such as sea chests and box coolers (Lamers, 2018), potentially replacing some of today's Marine Growth Prevention Systems (MGPS) based on chlorine-dosing or sacrificial anodic copper systems (Growcott, Kluza and Georgiades, 2017).

Finally, other methods that are relatively easy to implement on recreational boats, such as shrouding the hull with a physical barrier against fouling (Atalah *et al.*, 2016), hauling the vessel from the water while idle, or moving the vessel into freshwater for relatively long periods of time (Ralston and Swain, 2009), are currently not applicable for larger ships (Inglis, Floerl and Woods, 2012).

2.3. ‘The Battle of Adhesion’

Propagules and cells reach the surface of a hull by their own motility, or simply carried by currents and gravity (Cao *et al.*, 2011). At the solid surface, different species use different mechanisms to attach. Also, while individuals compete for space, humans ‘conspire’ to keep manmade structures free of fouling. The ‘Battle of Adhesion’ begins.

Single-celled organisms, such as bacteria and diatoms, secrete a mucous substance called Extracellular Polymeric Substance (EPS), rich in carbohydrates and proteins, enabling adhesion and the build-up of a biofilm. Once attached, some diatom species are able to ‘glide’ on their own mucous, and thus propagate to larger areas (Chiovitti, Dugdale and Wetherbee, 2006).

Meanwhile, propagules from macrofoulers may find the right chemical and other environmental cues on a surface, which signal them to attach. For example, zoospores (motile spores) of *Ulva* spp. actively select a point of attachment, after which they secrete a permanent adhesive (Callow and Callow, 2006). A similar process occurs for barnacle cypris larva, but these produce temporary adhesives that enable the cypris larvae to explore the surface until selecting a location for settlement. Finally, the larva metamorphose into juvenile barnacles and produce a permanent adhesive (Crisp *et al.*, 1985; Kamino, 2006).

At this point, our biofouling community is at an early, microfouling stage of development (individuals or colonies ≤ 1 mm in size). Several methods exist that may be used for testing how strongly these organisms have attached, i.e. their adhesion strength. For microfouling, testing has been performed in previous studies using hydrodynamic tests, such as turbulent channel flow apparatus (Schultz *et al.*, 2000) or impinging waterjets (Swain and Schultz, 1996; Finlay *et al.*, 2002; Cassé *et al.*, 2007). Forces may be calculated at the wall level, in terms of wall pressure and shear stress, i.e. areal forces in the normal and tangential directions to the solid surface (respectively), which are then used as a measure for adhesion strength, in Pascal units (N m^{-2}). In Paper I, it is suggested that such

values be used in matching cleaning forces, i.e. for in-water hull cleaning or grooming, to the adhesion strength of microfouling, as further discussed in sub-section 4.2. Further, a numerical study was carried out in Paper III on an immersed waterjet test setup, which was built and demonstrated in Paper IV.

Once macrofouling develops on a surface, it becomes increasingly difficult to completely remove it: e.g. barnacle shells may break before the occurrence of adhesive failure, i.e. at the bioadhesive-surface joint, meaning that adhesive strength is larger than the shell's cohesive strength. For macrofouling, a specific type of adhesion test was developed (ASTM D5618, 1994), which relies on applying shear force with a handheld force gauge on the side of each shell, until its base is dislodged. Thus, by taking the measured force and area of the basal plate into account (Figure 2d), shear adhesion strength can be calculated, also in Pascal units. However, the latter macrofouling adhesion strength cannot be directly compared to the microfouling adhesion strength from hydrodynamic tests, as further discussed in sub-section 4.2 and Paper I. Finally, the adhesion of oysters and tubeworms may be tested in a similar way as on barnacles, whereas mussels have the unique characteristic of issuing byssus threads that attach to a surface. The latter byssus threads may also be used for motility, by growing new threads and breaking old ones (Crisp *et al.*, 1985). Therefore, results from cleaning a surface heavily fouled with mussels will typically leave behind traces of those threads (Mortensen, 2013).

For advanced stages of fouling, and as individuals compete for space, barnacle shell morphology becomes more compact and tubeworms start growing upright from the hull, instead of along the hull (Naval Sea Systems Command, 2006). Also, as fouling reaches a certain density, epibiosis becomes increasingly common, with recent settlers growing on top of older layers of fouling. Epibiosis also allows species sensitive to copper to still be transported on hulls coated with AF paints, by attaching to copper-tolerant colonies used thus as a barrier against biocidal effects (Piola, Dafforn and Johnston, 2009).

2.4. Dead or alive

Chapter 2 has so far provided a brief description of marine biofouling, and the common prescriptions for preventing it. However, it would be incomplete without further mention to the biosecurity risks involved, and why potentially harmful marine fouling on ship hulls should be captured, 'dead or alive'.

By executing long-distance hauls and connecting otherwise segregated biogeographies, shipping represents a vector for invasion by non-indigenous species (NIS), with negative consequences for biodiversity, industries and human health (Sylvester *et al.*, 2011). Ships offer two ways in which aquatic species may be transferred: ballast water and biofouling. The risk of NIS transfer posed by hull fouling may be comparable to that of ballast water (Drake and Lodge, 2007). Additionally, transport hubs may provide a source for secondary spread of NIS into short-sea shipping routes (Floerl *et al.*, 2009).

The threat posed by ship's ballast water and sediments, as a vector for NIS and human pathogens, led to the ballast water and sediments IMO convention, which entered into force in 2017 (MEPC, 2019). Even though there are currently no equivalent international regulations on biofouling, only voluntary guidelines (IMO, 2011), some countries and jurisdictions such as New Zealand, Western Australia and California already took steps in the direction of regulating international vessels (Davidson *et al.*, 2016). More specifically, New Zealand has released requirements on acceptable levels of biofouling for arriving vessels (New Zealand Government, 2018), and California now requires all newly-built or recently-repaired inbound vessels to have a vessel-specific IMO Biofouling Management Plan in place (California State Lands Commission, 2017), which would otherwise be voluntary at this point (IMO, 2011).

In managing NIS vectors, it is generally preferable to manage risks at an aggregate level, with coarser but practical measures, such as defining an acceptable abundance and types of fouling, or enforcing good management practices, rather than proceed to micromanage individual target species using an 'unwanted list' (Davidson *et al.*, 2016; Tait and Larson, 2018). Following this practical approach to biosecurity risk management, it is commonly accepted that macrofouling represents a far greater risk than microfouling, i.e. marine slimes (Bell *et al.*, 2011; IMO, 2011). Thus, since fouling below slime cannot be currently managed by inspections from port-state authorities (see Scianni and Georgiades, 2019), uncaptured removal of microfouling is considered acceptable, provided that it does not damage the hull coating and that chemical discharges meet water quality standards (Australian Government, 2013; Morrisey *et al.*, 2013).

Higher biosecurity risks are associated with reactive in-water cleaning of macrofouling (Australian Government, 2013). If waste is not contained, the probability of organism survival is higher for in-water cleaning than it is for shore-based maintenance (Woods, Floerl and Jones, 2012). To mitigate such risks,

waste capture or inactivation technology should be further developed (IMO, 2011), with filtering down to 12.5- μm particle size being mentioned as an achievable standard for effluents from in-water cleaning (Morrisey and Woods, 2015), considerably lower than an earlier recommended 50- μm particle size (Australian Government, 2013). Further inactivation steps are also suggested, such as UV light, heat and biocides (Morrisey and Woods, 2015). Still, the capturing efficacy, in regards to amount and viability of organisms that may evade containment, should be further evaluated for current technology, as previous reviews identified several challenges in capturing waste from in-water cleaning (Floerl *et al.*, 2005; Morrisey and Woods, 2015).

Finally, niche areas on the hull, which are typically difficult to reach during in-water cleaning or grooming, are usually given lower priority from a vessel-performance perspective than from a biosecurity standpoint (Davidson *et al.*, 2016). This gap between industry and biosecurity perspectives is due to a meagre contribution of niche areas to ship resistance (except dry-dock block strips). Thus, compared to main areas on the hull, niche areas are less important for vessel propulsive performance, though still relevant for pumping and maintenance costs in the case of sea chests and internal pipework (Growcott, Kluza and Georgiades, 2017). However, niche areas are known as hotspots for hull fouling, and therefore associated with higher probability of NIS being present, compared to other areas on the hull (Davidson, Brown, Mark D Sytsma, *et al.*, 2009; Moser *et al.*, 2017). This issue will also be followed up in sub-section 4.5, along with recommendations on how to bridge the gap between industry priorities and biosecurity risks.

3. Hull fouling penalty

*One man therefore doth cooperate after one sort,
and another after another sort; but even he that
doth murmur, and to his power doth resist and
hinder; even he as much as any doth cooperate.
For of such also did the world stand in need.*

Marcus Aurelius Antoninus
(121-180 AD, *in Meditations* 6.37)

One of the main reasons shipping companies invest in hull maintenance has to do with the well-known problem of increased hull resistance due to hull surface roughness. The latter is not only due to an imperfect finish of the hull surface and coating, but also to a certain level of marine growth that eventually colonizes the hull, starting off as a thin slime layer, 'just detectable by touch' (Lewthwaite, Molland and Thomas, 1984). The fundamentals behind rough-hull penalties are reviewed in this chapter.

3.1. Turbulent boundary layers

The viscous flow around a travelling hull is composed of a boundary layer, within which velocity varies due to fluid viscosity. Setting the ship's hull as the reference, water velocity varies from zero at the hull (no-slip wall condition) to the ship's speed through water, which is measured on undisturbed water away from the hull (Larsson and Raven, 2010c) and may be exceeded at the boundary layer edge due to flow displacement (Larsson and Raven, 2010a).

Except for the very first few meters at the bow, the boundary layer around the hull is turbulent. This means that the flow is time-dependent, due to flow instabilities caused by inertia overcoming viscous forces at high enough Reynolds number Re_x , i.e. high enough ratio between distance from the bow, L_x , and the viscous length scale ν/U_{STW} , where ν is the kinematic viscosity and U_{STW} is the speed through water.

Flat plates with the same waterline length and wetted surface area as the hull, or alternatively same as a scaled model of a hull, can be used for representing the frictional resistance of a ship or of its model, by matching Reynolds number Re , based on waterline length, to that of the ship/model. This is a simplified approach that dates back to the work of William Froude, in the nineteenth century. More recently, it is recognized that the hull geometry alters the actual friction on the hull, which will therefore be different from that of a flat plate, being typically higher on the hull. This difference is given by a correction factor, i.e. the form factor on friction (Kouh, Chen and Chau, 2009; Larsson and Raven, 2010c).

In addition to friction, the total hull resistance, i.e. sum of forces opposing the ship's movement, is also composed of pressure resistance, which arises from both the disturbance of the free surface, i.e. wave-making resistance, and a pressure deficit at the aft body due to the presence of a boundary layer, i.e. viscous pressure resistance (Larsson and Raven, 2010a). The latter viscous pressure arises from displacement of streamlines by the boundary layer flow, which reduces the pressure recovery at aft of the hull, thence contributing to resistance. In short, the total hydrodynamic resistance can be expressed by the sum of dimensionless coefficients $C = R / (\frac{1}{2}\rho U_{STW}^2 S)$, where R , ρ , U_{STW} and S are the hydrodynamic resistance (in N), fluid density, speed through water and wetted surface area of the hull (respectively), yielding:

$$C_T = (1 + K_F) \times C_{F0} + C_{VP} + C_W \quad (1)$$

where C_T is the total hydrodynamic resistance coefficient, C_{F0} the flat plate frictional resistance coefficient, typically obtained from available friction lines, K_F is the form factor on friction, accounting for differences between flat-plate and hull frictional resistance, C_{VP} is the viscous pressure resistance coefficient, and C_W is the wave-making resistance coefficient. The latter wave-making is typically derived from model-scale resistance tests in a towing tank (ITTC, 2014), by running the model at the same Froude number Fr as the ship (Larsson and Raven, 2010b). Finally, an alternative way to present Equation 1 is by merging both form effect on friction and form effect on pressure into a single form factor K (Larsson and Raven, 2010c):

$$C_T = (1 + K) \times C_{F0} + C_W \quad (2)$$

where K is also determined experimentally at the model scale, using Prohaska's method (Larsson and Raven, 2010b), or else from double-body Computational Fluid Dynamics (CFD) simulations on that specific hull (Kouh, Chen and Chau, 2009). For an approximate estimate of $(1 + K) \times C_{F0}$, the latter double-body simulations eliminate wave-making resistance ($C_W = 0$, in Equation 2) by replacing the free surface by a symmetry boundary condition at the waterline.

The consequences of the above decomposition on hull roughness penalties are explored in Paper II, starting from the hypothesis of roughness effects limited to the flat plate frictional component, C_{F0} , as introduced in the next sub-section.

3.2. Roughness effects on flat plates and ships

The inner-scaled⁽³⁾ velocity profile of a turbulent boundary layer over a flat plate consists of four regions. Starting from the wall and moving towards the boundary layer edge, these regions correspond to: (1) viscous sublayer, where velocity u varies linearly with distance from the wall y , i.e. $u^+ = y^+$, (2) buffer layer, where the velocity profile departs from linear, (3) logarithmic region, where u^+ is a logarithmic function of y^+ , and (4) a wake region, corresponding to the outer region of the boundary layer (Larsson and Raven, 2010c).

The above holds for a boundary layer developed over a smooth surface, i.e. when roughness elements are small enough so that flow perturbations are damped out by viscosity (Flack and Schultz, 2014). The definition of a smooth surface is thus dependent not only on geometrical parameters of the surface, such as roughness element height, but also on the relation between surface topography and flow parameters. Thus, a common definition of smooth-surface behaviour is when roughness elements are contained within a certain critical height, at about the thickness of the viscous sublayer (Larsson and Raven, 2010c). Still, there has been some contention over the validity of this concept of a critical roughness height (Bradshaw, 2000). The latter contention might have originated from differences between disparate types of roughness (Flack, Schultz and Rose, 2012), and also the fact that a surface cannot be fully described, in

³ Inner-scaled variables are denoted with a superscript '+', for example: $u^+ = u/u_\tau$ for dimensionless velocity, and $y^+ = y/(v/u_\tau)$ for dimensionless distance from the wall, where inner-scaling variables are friction velocity u_τ and viscous length v/u_τ .

regards to its hydrodynamic effects, using a single parameter, such as roughness height (Grigson, 1987; Flack and Schultz, 2014).

Whether one accepts or not the existence of a critical height, a widely-recognized effect of surface roughness is the downward shift in the logarithmic region of the boundary layer (Bradshaw, 2000), caused by shedding of eddies, and consequent viscous and form drag over roughness elements. This downward shift is denoted by the roughness function, ΔU^+ , which is subtracted from the smooth logarithmic velocity profile (Cal *et al.*, 2009; Flack and Schultz, 2014):

$$u^+ = \frac{1}{\kappa} \ln[(y + \varepsilon)^+] + C - \Delta U^+ \quad (3)$$

where ε is the wall origin error, included as a fitted parameter due to it being impossible to set an unequivocal y -origin on a rough surface (Lewthwaite, Molland and Thomas, 1984; Perry and Li, 1990), C is the smooth wall intercept, and ΔU^+ is the roughness function, i.e. the downward shift in the velocity profile. The latter is typically expressed as a function of roughness Reynolds number, $k^+ = k \cdot u_\tau / \nu$, based on an arbitrary roughness height k . The latter roughness height is arbitrary, since two different surfaces with approximately the same peak-to-valley roughness height $k = k_t(\text{surface 1}) \approx k_t(\text{surface 2})$, but different roughness topographies, may differ widely in terms of hydraulic effects, i.e. $\Delta U^+(\text{surface 1}) \neq \Delta U^+(\text{surface 2})$, as further discussed in the next sub-section.

Finally, and most importantly, provided that outer-layer similarity holds, i.e. no significant roughness effects are detected on the outer layer of the boundary layer (Jimenez, 2004; Schultz and Flack, 2007), the roughness function ΔU^+ may be used in modelling roughness effects on the flow around large objects, such as flat plates and ships (Schultz, 2007; Demirel, Turan and Incecik, 2017).

3.3. Roughness functions: devil is in detail

In the previous sub-section, an overview was given on the roughness effects on boundary-layer flow, which are quantified using a roughness function $\Delta U^+ = \Delta U^+(k^+)$. From available data on the roughness function of a given surface, it is then possible to determine resistance penalties for the full-scale ship, by implementing $\Delta U^+ = \Delta U^+(k^+)$ in the simplest flat-plate similarity-law scaling method – Granville method – as described in Schultz (2007), or else by implementing this roughness function into wall functions in CFD simulations of

the viscous flow around the ship (Demirel, Turan and Incecik, 2017). However, there are at least two practical challenges in accurately modelling roughness penalties at the ship scale: (1) an uneven distribution of roughness across the hull, and (2) unknown roughness functions and scaling parameters for each new surface topography. These two challenges are discussed in this sub-section. A third challenge is added on how to deal with missing form effects in flat-plate methods, e.g. Granville method, as discussed in sub-section 4.4 and Paper II.

Regarding the first challenge, roughness is usually distributed unevenly across a newly painted hull, and certainly more so on fouled hulls (Schultz, 2007; Townsin, 2013; Swain and Lund, 2016). However, this might be the easiest to solve, considering that, in a CFD simulation, it is in principle possible to implement geometry parts with varying roughness properties ($\Delta U^+ = \Delta U^+(k^+)$, and k value).

Regarding the second challenge, the roughness function ΔU^+ must be determined experimentally for each new type of surface found on ship hulls (Leer-Andersen, 2018; Speranza *et al.*, 2019). Thus, in spite of continued efforts in search of ever more widely-applicable correlations between roughness function ΔU^+ and directly-measured surface roughness parameters/statistics (Grigson, 1992; Schultz, 2004; Flack and Schultz, 2010; Yeginbayeva and Atlar, 2018), there is still no universal roughness function that would hold for all types of roughness on ship hulls (Speranza *et al.*, 2019).

To illustrate this last challenge, examples of roughness-function results from previous studies are reproduced in Figure 3 (Johansson, 1984; Schultz and Swain, 1999; Schultz, 2000, 2004; Shockling, Allen and Smits, 2006; Schultz and Flack, 2007; Demirel *et al.*, 2015; Schultz *et al.*, 2015; Ünal, 2015; Yeginbayeva and Atlar, 2018; Niebles Atencio and Chernoray, 2019), for different types of surface roughness, ranging from antifouling (AF) and foul-release coatings (FR), to fouled surfaces such as biofilms (microfouling), barnacles and filamentous alga (macrofouling). Also shown are the main types of roughness function that different authors have used for fitting their data, namely Colebrook-type functions (Johansson, 1984; Grigson, 1992), uniform sand-grain roughness function (Nikuradse, 1933; Cebeci and Bradshaw, 1977) and Demirel *et al.*'s roughness function based on data used by Schultz (Schultz, 2007; Demirel, Turan and Incecik, 2017). In this plot, large differences are observed between studies, where comparable ΔU^+ values are obtained at disparate values of arbitrary k , which is

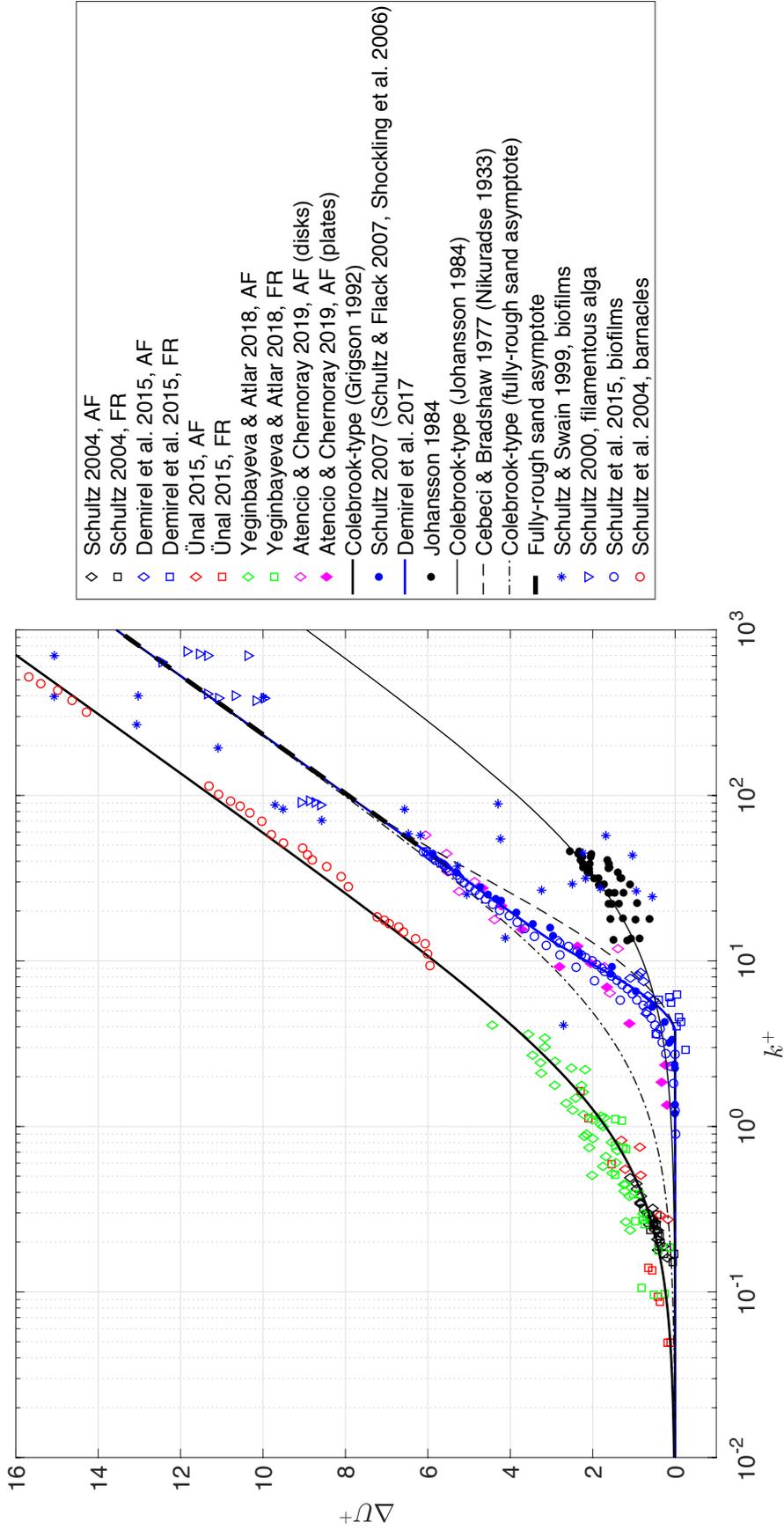


Figure 3 – Roughness functions, ΔU^+ , for different types of roughness Reynolds number k^+ , based on arbitrary roughness height k .

defined differently within each study. Also, it can be observed that only a few studies reach the fully-rough regime, in which ΔU^+ data approaches a linear asymptote (Schultz and Swain, 1999; Schultz, 2000, 2004; Schultz *et al.*, 2015). The latter behaviour is associated with form drag over roughness element becoming the dominant mechanism for momentum deficit. For other studies, the roughness function is within the transitionally-rough regime, i.e. in the transition between hydraulically smooth, i.e. $\Delta U^+ = 0$, and a fully-rough linear-asymptotic behaviour. In this transitional regime, both form and viscous drag over roughness elements play a role (Flack, Schultz and Rose, 2012).

Further insight into the above ΔU^+ data is gained by collapsing the three ΔU^+ functions in the fully-rough regime (i.e. collapsing Colebrook-type, uniform sand-grain roughness, and Demirel *et al.*'s roughness functions), as presented in Figure 4. Collapsing in the fully-rough regime is currently achieved by multiplying the arbitrary k values in Figure 3 by a suitable scaling factor. This scaling operation moves all data points along the logarithmic horizontal axis, so that all fully-rough asymptotes collapse with that of sand-grain roughness, herein selecting equivalent sand-grain roughness k_s as a common currency between disparate types of roughness (Bradshaw, 2000). Results scaled in this fashion still show a wide range of variation between studies in regard to the onset of roughness effects, i.e. the k_s^+ value at which roughness function ΔU^+ departs from zero, as well as in regard to the shape of the curve in the transitionally-rough regime: e.g. at $k_s^+ = 4$, ΔU^+ spans between 0 and ~ 2 (Figure 4). Further, it is noted that results from foul-free AF and FR coatings tend to follow a Colebrook-type roughness function, with reasonable agreement between most studies, whereas fouled samples tend to have an inflectional behaviour, closer to that of the sand-grain roughness function (Nikuradse, 1933; Cebeci and Bradshaw, 1977). Finally, even though there is significant spread in the earlier works on biofilms and filamentous algal fouling (Schultz and Swain, 1999; Schultz, 2000), later studies on both hard and soft fouling (Schultz, 2004; Schultz *et al.*, 2015) are well represented by Demirel *et al.*'s roughness function (Figure 4, blue line).

Regarding soft hull fouling, such as biofilms and filamentous alga, further complexity arises due to flow compliance, i.e. varying morphology under flow, including oscillating or flapping streamers and filaments (Stoodley *et al.*, 1998; Townsin, 2003). These phenomena probably have a significant hydrodynamic effect, considering several examples in which seemingly 'harmless' biofilms caused surprisingly high penalties in terms of frictional drag: Lewthwaite *et al.* (1984) reported local increase in skin friction of 25-80% for slimes ranging from

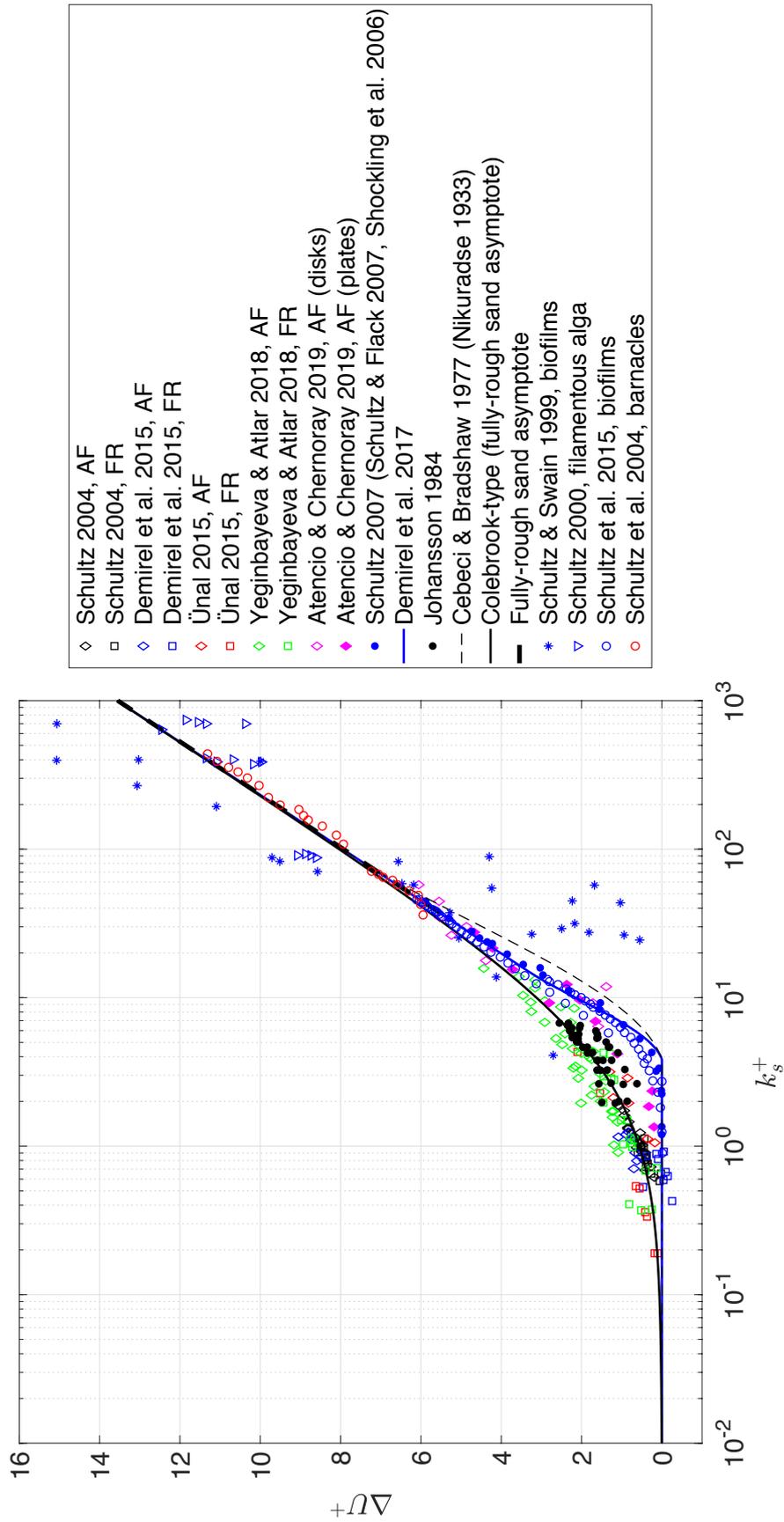


Figure 4 – Roughness functions, ΔU^+ , for different types of roughness, as a function of roughness Reynolds number k_s^+ , based on equivalent sand-grain roughness height k_s .

incipient biofilms, detectable only by touch, to 1-mm thick biofilms; more recently, Murphy et al. (2019) reported an equivalent sand-grain roughness height of close to ~ 9 mm for a mere 1.7-mm thick biofilm, which is attributed to flapping of streamers and compliance of the biofilm.

Since no universal roughness function can be obtained for different hull conditions by a simple scaling parameter, as observed by disparate function shapes in the transitionally-rough regime (Figure 4), it seems idle to search for a universal correlation between surface roughness statistics and an equivalent sand-grain roughness height. The other option would be some way of accounting for the shape of the roughness function into a universal correlation, which is not trivial given an admittedly-high diversity of function shapes (Grigson, 1992).

Still, for practical applications, it seems that ΔU^+ values can still be useful in deriving indicators of hull performance, as further suggested in Paper V. In this paper, in-service vessel performance data is used in estimating the equivalent sand-grain roughness height for each data point in time, as further discussed in section 4.4.

4. Results and discussion

*The world cannot be understood without numbers.
And it cannot be understood with numbers alone.*

Hans Rosling (*in* 'Factfulness', 2018)

In an ideal world, a ship technical manager would have access to accurate figures on how biofouling is penalizing vessel performance at a given point in time. The same manager would also know when the next in-water cleaning event should take place, whether to clean niche areas, and how high should cleaning forces be. In such idealized world, legislators and local decision-makers would have access to detailed and evidence-based assessment on risks involved in issuing specific permits for in-water maintenance, or on the costs and benefits of incentivizing the shipping industry towards improved technology. In reality, these actors must deal with missing or inaccurate data, and make decisions within bounded rationality (Johnson and Andersson, 2014).

What *do* available numbers tell us? And what do these numbers fail to tell? After briefly discussing the contribution and main outcome from each appended paper (sub-section 4.1), the current chapter discusses, in the following order: adhesion strength and in-water cleaning forces (sub-section 4.2 and 4.3, with reference to Papers I, III and IV), evaluating the success of hull management approaches (sub-section 4.4, with reference to Papers II and V), current methodological aspects (sub-section 4.5) and, finally, an outlook on future research and development (sub-section 4.6).

4.1. Contribution and outcome from appended papers

The main contribution and outcome from each of the appended papers are here presented, as well as how these can help improve current practices.

Paper I is a review article on biofouling adhesion strength values from available literature, suggesting that early stages of fouling should be targeted for cleaning, and identifying some methodological issues in current methods of

adhesion strength testing. The outcome is both of relevance for testing of coatings in terms of their foul-release properties, and also as a guidance for designers and users of hull cleaning devices (selection of cleaning forces).

Paper II investigates whether effects from hull form, i.e. effects arising from hull-shape design, should be considered in determining hull-roughness resistance penalties on full-scale vessels. Form effects on roughness penalties were confirmed for a containership travelling at a lower speed, meaning that penalties would have been underestimated using a simplified CFD flat-plate model for friction. However, at higher vessel speed, changes to other resistance components (wave-making resistance) were shown to cancel out the form effects on roughness penalty, bringing hull resistance penalties down towards those of a flat plate. Further, it was shown that penalty estimates from similarity-law scaling method / Granville method, which also assumes a flat-plate model for friction, could not be improved by applying a form-factor correction. Therefore, the Granville method can be used directly in studying the economics of underwater hull maintenance, e.g. in analysing vessel performance data as demonstrated further in Paper V.

In **Paper III**, adhesion strength testing is further considered from the perspective of obtaining an absolute reference for cleaning forces to be used in in-water hull cleaning. Drawing inspiration from the approach of using adhesion strength data to predict detachment of biofouling while a vessel is underway (Schultz *et al.*, 2003), semi-empirical formulas were revised in Paper III for determining forces under immersed waterjets. Adhesion strength testing with waterjets benefits from portability and higher forces, when compared to other methods such as turbulent channel flow apparatuses. Based on collection of results for impinging jets from available literature, as well as original CFD calculations, Paper III provides guidance on how waterjet adhesion strength tests should be conducted under immersed conditions, as further demonstrated in Paper IV.

Paper IV demonstrates the applicability of an immersed waterjet setup for determining adhesion strength of biofouling on an absolute scale, relying on semi-empirical formulas derived in Paper III. Minimal forces applied monthly/bi-monthly were shown to decrease the level of fouling, while causing no significant damage to fouling-control coatings. Further, repeated cleaning with an immersed waterjet (bi-monthly / monthly) did select for tenacious biofilms, as also reported in previous literature. Such tenacious biofilms suggest that biofouling pre-exposed

to flow (e.g. on an active vessel) may possess different mechanical properties compared to biofouling grown under static conditions.

Finally, **Paper V** demonstrates that existing indicators of vessel performance, such as percentage speed loss or percentage power increase, are tied to vessel design and vessel speed, among other operational parameters. Thus, aiming at eliminating these effects, this paper puts forward modelling of hull roughness height, as a physical representation of hull condition that would not depend on other vessel characteristics. Limitations to this approach include inadequacy in dealing with unphysical negative values of power penalty, and challenges in validating the method against full-scale trials. In spite of these limitations, Paper V demonstrates qualitative agreement between the new indicator and estimates of hull condition based on diving inspections. Thus, while power penalties are still valuable for economic analyses on underwater hull maintenance, roughness height can be further used in predicting fuel consumption under varying operational conditions, as well as enabling future comparisons between vessels.

Results in appended papers are further discussed below in this chapter.

4.2. Adhesion of marine biofouling

Answering research question 1 regarding **the cleaning forces required for removing marine fouling**, shear forces are in the range 8-275 Pa for microfouling on foul-release coatings (at least 80% removal), and up to 0.03-2.2 MPa for macrofouling, depending on coating type (Paper I). Paper IV further concludes that shear forces of ~1.3 kPa would be required to keep fouling to an incipient slime on both a biocidal and a foul-release coating. Additionally, answering to research question 2 on **how required forces relate to the timing of the cleaning**, it is argued in Paper I that forces may increase as macrofouling becomes established, raising issues such as increased risk of coating damage and incomplete removal of calcareous shell fouling. Finally, both experimental and numerical methods for determining cleaning forces are reviewed and compared in Paper III.

In Paper I, the adhesion strength of different types of fouling was reviewed, i.e. that of main groups of marine fouling on representative types of hull coatings. The rationale behind this was to investigate how forces reported in previous work could be utilized in minimizing in-water cleaning forces, thus avoiding damage to hull coatings during cleaning. Gaps were identified, in regards to (1) applicability

of such approach, (2) establishment of a consistent definition of adhesion strength, and (3) availability of data on adhesion strength.

First and foremost, applicability of matching cleaning forces to the adhesion strength of fouling depends on removal efficacy. As reviewed in Paper I, this efficacy is not satisfactory in the case for hard fouling developed on coatings with no foul-release properties, such as inert or conventional biocidal coatings, due to occurrence of cohesive failure of the shell, instead of adhesive failure. Thus, in the case of barnacles on a coating with limited foul-release properties, the upper shells, and a possibly a fraction of the basal plate, may fracture before complete detachment of the adhesive from the coating (Berglin *et al.*, 2001). Paper I thus concludes that hull management should avoid, as much as possible, in-water cleaning on hulls exhibiting macrofouling, as remaining basal plates may lead to hull resistance penalties and also serve as a cue for subsequent recruitment (Anil *et al.*, 2010). An illustrative example is given in Figure 5, where barnacle base plates remained after reactive cleaning on a failing biocidal coating (Figure 5a), and heavy fouling returned within four months (Figure 5b). Use of more aggressive cleaning methods may also lead to coating damage on foul-release coatings (Townsin and Anderson, 2009), and also to depletion of biocidal coatings, as observed in Figure 5d, where corrosion and deeper layers of coating are visible after a second reactive cleaning. Damage and wear to AF coatings means an increased burden on the management of waste streams containing paint debris and biocides (Schottle and Brown, 2007; Earley *et al.*, 2014). Therefore, preference is given, based on the outcome of Paper I, to targeting early stages of fouling, i.e. microfouling, as a way of reducing the risk of negative impacts on the coating and the local environment, as well as preventing further growth. In practice, this differs from reactive approaches to hull management currently followed by some shipping segments, as further observed in Paper V.

Further, it is important that adhesion strength values be translatable into full-scale cleaning parameters. In Paper I, adhesion strength results are compiled from several studies. In compiling these data, it was quickly realized that macro- and microfouling adhesion strength values are not directly comparable. The reason for this incompatibility has to do with the use of different methods in testing of macro- and microfouling: macrofoulers are typically tested using a handheld force gauge (ASTM D5618, 1994), whereas microfouling is tested using

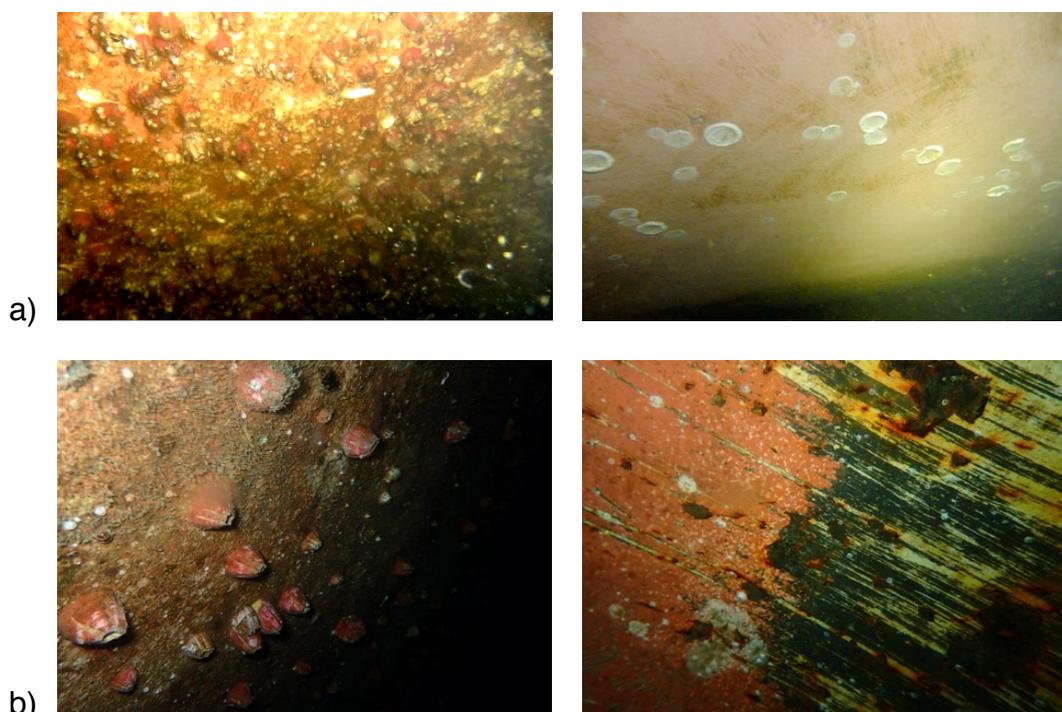


Figure 5 – Underwater photographs of the flat bottom of a Panamax tanker with a failing biocidal coating, **before / after in-water hull cleaning** (left / right-hand side, respectively), on two consecutive cleaning events (a, b) spaced by a period of less than four months. Height of barnacles is ~6-10 cm. Images courtesy of Marininvest Shipping AB (Gothenburg, Sweden; reproduced with permission).

hydrodynamic methods (Schultz *et al.*, 2000). In the first case, tangential areal forces, applied using a handheld gauge to the base of barnacles (or other hard macrofoulers) are not consistent with hydrodynamic pressure and shear stress values reported in hydrodynamic approaches for microfouling, which are obtained at a smooth wall (Swain and Schultz, 1996; Schultz *et al.*, 2000; Finlay *et al.*, 2002). Thus, adhesion strength values reviewed in Paper I for macrofouling, in the range 0.03-2.2 MPa, cannot be directly compared to adhesion strength values for microfouling, in the range 8-275 Pa (80% removal efficacy), due to fundamentally different methods used. Thus, if adhesion strength values cannot be compared even among themselves, how can we ever hope to compare these to the forces imparted by full-scale cleaning devices? Such hope of matching cleaning forces still remains, as discussed next.

For macrofouling, handheld-gauge adhesion strength values (ASTM D5618, 1994) can be directly compared to the forces applied by cleaning devices (e.g.

brush systems) on ‘instrumented studs’, i.e. probes of barnacle size and shape that are connected, via a pivot arm, to a load cell that enables shear force measurements (Holm, Haslbeck and Horinek, 2003). Using this technique, previous work had found that their grooming brush tool applies a 0.011-MPa shear force, which could only possibly remove ‘minimally adhered barnacles’ (Tribou and Swain, 2015), since this cleaning force is somewhat below average adhesion values, in the range 0.03-2.2 MPa for macrofouling (Paper I).

For microfouling, studies on adhesion strength report hydrodynamic forces on a smooth wall, namely the wall shear stress exerted under turbulent channel flow (Schultz *et al.*, 2000), or else by reporting the surface pressure and wall shear stress under an impinging waterjet (Finlay *et al.*, 2002). Wall shear stress values may be directly compared to conditions experienced on a travelling hull, thus being relevant in the prediction of foul-release coating performance against microfouling at the ship scale (Schultz *et al.*, 2003).

Compared to existing channel-flow setups, relatively high forces are easier to achieve using waterjet setups (Finlay *et al.*, 2002). Also, as discussed in Paper III, an impinging jet results in superimposed pressure and wall shear-stress gradients, with a localized pressure increase near the jet’s impingement and a larger radius for exerted maximum wall shear stress. This pattern resembles more closely the flow under waterjet cleaning nozzles, which are increasingly used as cleaning method in commercial cleaning devices, as an alternative to rotating brushes (Morrisey and Woods, 2015). However, as discussed in Paper III, a semi-empirical formula previously used in determining wall shear stress under impinging jets (Finlay *et al.*, 2002; as well as in Paper I) did not take into account that: (1) waterjets in air, as used in microfouling adhesion testing in previous studies, have lower momentum losses than immersed waterjets used in deriving semi-empirical formulas for wall forces (Beltaos and Rajaratnam, 1974), due to entrainment of surrounding fluid in the latter immersed jets; and (2) the wall shear stress under an impinging jet is also a function of the Reynolds number based on nozzle diameter, i.e. wall forces depend on fluid viscosity (Paper III).

Answering research question 3 **on how to quantify cleaning forces on an absolute scale**, Paper III investigated the magnitude of wall pressure and shear forces under impinging jets, by reviewing previous work and building a numerical CFD model (Computational Fluid Dynamics) of immersed jets using single-phase RANS simulations (Reynolds Averaged Navier-Stokes). This study suggested a new set of semi-empirical formulas. These formulas are used in determining wall

forces based on only a few adhesion-strength test parameters, such as nozzle diameter, stand-off distance, flowrate and fluid properties. Furthermore, testing of microfouling adhesion strength should be performed using *immersed* waterjets, so that the semi-empirical formulas presented in Paper III remain valid.

The latter semi-empirical formulas were then applied in Paper IV to field data from immersed waterjet testing of microfouling adhesion strength on commercial hull coatings. Adhesion strength values, as presented in Figure 6 of Paper IV, correspond to up to $\sim 1,300$ Pa in wall shear stress, which is about four times as high as the maximum value of ~ 300 Pa reviewed from previous literature (Paper I). This difference may arise from underestimated wall shear stress in previous studies (including Paper I), due to the use of a semi-empirical formula for immersed jets that is not valid for water-in-air jet apparatuses (Beltaos and Rajaratnam, 1974). Differences could also be due to different percentage-removal criteria used in Paper I, versus the criterion of a visually clean coating, used in Paper IV.

In analogy with rotating-brush grooming systems, which were studied using ‘instrumented studs’ for comparison with adhesion-strength values of macrofouling (Holm, Haslbeck and Horinek, 2003; Tribou and Swain, 2015), tailored experimental or numerical studies on full-scale waterjet cleaning devices would be required. These studies would use methods as reviewed in Paper III, such as CFD simulations or experimental techniques, e.g. hot-film sensors or more advanced electrochemical techniques. Such studies are required in order to calibrate full-scale devices according to the adhesion strength values of microfouling (Figure 6 of Paper IV).

Finally, with the above definitions of adhesion strength for each of macro- and microfouling, only one last gap remains as identified in Paper I, that of data availability. Lack of adhesion strength data is noted for the most common type of coatings, i.e. biocidal anti-fouling coatings, and for complex naturally-occurring multispecies communities. Paper IV aimed at starting to fill this last gap, already using the newly-proposed immersed waterjet setup.

4.3. Hull grooming approaches

As further argued in Paper I, microfouling should be targeted for cleaning, in detriment of macrofouling, which is in line with other studies conducted on hull grooming approaches, i.e. gentle- and frequent-cleaning approaches (Hearin *et al.*, 2015; Tribou and Swain, 2015, 2017). However, **what are the effects of minimal cleaning forces on hull coatings**, including coating deterioration and biocide emissions to water? (research question 4).

Paper IV aimed at answering this question on effects of cleaning forces on coatings by visual inspection of paint damage, thickness measurements for determining paint wear, and cross-section microscopy-imaging of coating samples for determining the condition of the top coating. Paint damage included chipping, scratches or pitting corrosion at less than 1% cover, and there were no significant differences between cleaning treatments (bimonthly/monthly cleaning frequency). Also, an average wear of $\sim 30\text{-}35 \mu\text{m}/\text{year}$ was observed across all cleaning treatments, with no significant change with increasing cleaning frequency (bimonthly/monthly) or nozzle translation speed ($0.01\text{-}0.03 \text{ cm/s}$). Finally, the condition of the top coatings was similar for both non-cleaned and monthly-cleaned panels, with a visible copper-depleted top layer, also referred to as leached layer, as shown from SEM images (Surface Electron Microscopy) combined with EDX chemical analysis (Energy-Dispersive X-Ray analysis). This leached layer was $\sim 20\text{-}30 \mu\text{m}$ -thick at the end of one year of immersion, adding to the paint wear rate of $\sim 30\text{-}35 \mu\text{m}/\text{year}$, which is in the same order of magnitude. The later values mean an average biocide release rate to water of $\sim 13 \mu\text{g Cu} / \text{cm}^2 / \text{day}$ from paint wear alone, and up to $\sim 20 \mu\text{g Cu} / \text{cm}^2 / \text{day}$ if the biocide release from the leached layer is also taken into account. Since paint damage, wear and leached layer did not change significantly with increasing cleaning frequency, the cleanings had a non-detectable effect on the coating condition. However, there are still unknown uncertainties related to the presence of tenacious biofilms, as further discussed in Paper IV.

For comparison with current results, a grooming approach was shown to significantly reduce the level of fouling compared to ungroomed panels in a six-year study conducted in Florida, USA, and also to cause only minimal wear to an ablative AF coating (Tribou and Swain, 2017). According to the same authors, the alternative of reactively cleaning US-Navy ships would lead to a considerably higher coating wear, due to more aggressive methods used in yearly reactive cleanings, with more than triple the coating wear using reactive cleaning

compared to a grooming approach (Tribou and Swain, 2017). A higher coating wear (and damage) consequently leads to a higher risk of chemical pollution and concerns in terms of management of waste streams from in-water reactive cleaning, due to generated paint debris and pulse release of biocides.

Finally, a grooming approach is not without its challenges, as observed also in Paper IV with resilient, tenacious biofilms eventually forming as a result of frequent and gentle cleanings, in this case monthly/bi-monthly cleanings in Swedish waters (Gothenburg, West coast of Sweden). Results from Paper IV mirror previous findings from hull grooming in regions with higher fouling pressure (Hearin *et al.*, 2016). It is not yet clear in which way such biofilms influence coating performance, since e.g. biofilms may have a negative impact on biocide diffusion, but also contribute to increasing the rate of dissolution of biocides in seawater (Howell, 2009).

Limitations of the current approaches in Paper IV will be further discussed in in sub-section 4.5 Methodology. Here it suffices to mention that, though long-term effects remain to be studied, mid-term results presented in Paper IV (one-year study) seem to indicate hull grooming as a suitable approach to reduce the level of fouling, while having a minimal impact on coating wear and damage. Still, recommended forces reported in Paper IV need to be translated into full-scale calibration of hull cleaning devices, as outlined previously in sub-section 4.2 and, in more detail, in Paper III.

4.4. Evaluating hull management approaches

As discussed in the previous sub-section, proactive in-water maintenance approaches may bring benefits in terms of limiting marine growth on the hull, extending the lifetime of coatings, and reducing the load of paint components into the marine environment (Papers I, III and IV). However, frequent in-water maintenance may entail significant costs for shipowners, which need to be weighed against any long-term vessel performance gains. Further, there could be other incentives for maintenance of niche areas, such as discounts in port and fairway fees for less-fouled hulls, or sanctions for heavily-fouled hulls in certain jurisdictions (e.g. New Zealand).

The current sub-section includes a discussion on current tools for quantifying the impact of maintenance on vessel performance (Papers II and V), answering research question 5 on **how to quantify resistance and powering savings**.

Papers II and V follow two approaches with opposite starting points: Paper II starts from an assumed or observed hull condition, and aims at determining hull resistance penalties; Paper V instead applies methods discussed in Paper II in an iterative procedure to determine the hull condition that gave rise to measured penalties, using onboard collected data as the starting point. Paper II demonstrates that, for the fastest method of estimating hull resistance penalties, i.e. the flat-plate Granville method, no improvement can be achieved in terms of agreement with CFD results by taking hull form factor into account. This finding from Paper II is used in Paper V, which applies the Granville method for penalty estimation, without any correction for hull form. Paper V further proposes a new indicator, which enables a direct comparison between vessels, by expressing performance as a hydraulic roughness height. The two approaches, namely the scaling-up procedure from condition to penalty (Paper II) and the reverse procedure of using of in-service performance monitoring for estimating hull/propeller condition (Paper V), should be seen as complementary.

The form-factor-on-penalty hypothesis put forward in Paper II can be summarized as follows: assuming that hull roughness affects primarily the flat-plate frictional resistance of a ship, and that this resistance component translates into viscous resistance on the hull shape through a constant factor of $1 + K$ (Equation 2), the resulting roughness penalty on ship hull resistance, ΔC_T , would correspond to the product between $1 + K$ and flat-plate penalty ΔC_{F0} . This hypothesis would amount to adding the flat-plate penalty ΔC_{F0} directly to the flat-plate resistance coefficient C_{F0} in Equation 2, yielding:

$$C_T = (1 + K) \times C_{F0} + C_W + \Delta C_T \quad (4.1)$$

$$C_T = (1 + K) \times (C_{F0} + \Delta C_{F0}) + C_W \quad (4.2)$$

This approach differs from that of previous studies, where flat-plate penalty ΔC_{F0} is not multiplied by any form factor (Schultz, 2007; Demirel, Turan and Incecik, 2017). According to the form-factor-on-penalty hypothesis in Paper II, ignoring ship hull form would lead to an underestimation of roughness penalties, since form factor K is typically positive, due to an increase in friction from flat plate to hull shape, as well as a positive effect of the boundary layer on pressure resistance, i.e. viscous pressure resistance (Kouh, Chen and Chau, 2009).

This form-factor hypothesis was tested in Paper II by re-analysing publicly-available data originally published in Demirel, Turan and Incecik (2017). The latter

authors performed CFD simulations on the towing resistance of a specific hull shape, the KRISO containership, as well as its equivalent flat plate, with varying equivalent sand-grain roughness height. Thus, by decomposing resistance and comparing frictional penalties on the hull shape to those simulated on the equivalent flat plate, a fairly constant form factor on frictional penalties of ~ 0.05 could be obtained from Demirel et al.'s data (Table 3 in Paper II). However, Paper II also demonstrated that a form factor on *total penalties*, including viscous pressure resistance, cannot be generalized for all vessel speeds. At a speed of 19 knots, the form factor on roughness penalties was ~ 0.06 (Table 5 in Paper II), not far from the approximate form factor of 0.1 for this hull (Castro, Carrica and Stern, 2011), which however is not the case for a higher speed of 24 knots, with an approximately *null* form factor on flat plate penalties at this higher speed. The latter observation was finally demonstrated in Paper II as being due to an invalid initial assumption, according to which roughness would *only* effect the flat-plate frictional resistance. Indeed, by increasing vessel speed, the wave-making resistance component C_W in Equation 4 increases considerably, and this wave-making component was shown by Demirel, Turan and Incecik (2017) to decrease with increasing hull roughness. The latter effect on C_W was corroborated by a decreasing wave amplitude with increasing hull roughness height (Demirel, Turan and Incecik, 2017; Song, Demirel and Atlar, 2019). Such viscous effects on wave-making component C_W , which likely arise from a lower viscous pressure recovery at the aft of a rough hull (compared to a smooth one), are pointed out in Paper II as the cause for cancelling out of form effects on roughness at the higher speed of 24 knots. Paper II thus concludes that the form-factor-on-penalty hypothesis cannot be generalized for all vessel speeds. Furthermore, the flat-plate Granville method was shown to yield more accurate results when no form-factor correction is used (Figure 3 in Paper II).

Scaling-up procedures are of great interest for quantifying the range of roughness penalties on resistance and powering of a ship (Schultz, 2007). Unfortunately, available lab results on the hydraulic effects of different types of surface cannot be expected to represent all in-service coating and fouling conditions observed on actual vessels. This difficulty is not least due to the endless variety of roughness topographies, flow-compliant roughness profiles, as well as non-uniformity of roughness distribution across the hull (Schultz, 2007; Murphy *et al.*, 2019; Speranza *et al.*, 2019).

The lack of representative data for specific hull conditions seems thus to limit the usefulness of scaling-up procedures (e.g. CFD or Granville method), since

these require two inputs that are usually missing for in-service vessels: (1) a roughness-function curve $\Delta U^+ = \Delta U^+(k^+)$, which should hold in the transitionally-rough regime for a specific roughness type, and (2) a roughness parameter k and its spatial distribution on the hull, such as an equivalent sand-grain roughness height k_s , used in deriving the actual ΔU^+ value from the roughness function $\Delta U^+ = \Delta U^+(k_s^+)$ under specified flow conditions. Since these inputs must be determined experimentally (Speranza *et al.*, 2019) and this is not a viable option for in-service vessels, the scaling-up approach seems to be limited to crude estimates, such as those relying on databases of hydraulic parameters for different sets of hull conditions (Leer-Andersen, 2018) or relying on approximate correlations based on main roughness parameters, such as fouling height and percentage cover (Schultz, 2004; Schultz *et al.*, 2015).

It is however worth noticing that, for all roughness types covered in section 3.3, the effect on the boundary layer, as measured by ΔU^+ , is an unequivocal measure of hydraulic penalties under given flow conditions (Figure 4), namely at a given speed and distance from the bow. Paper V takes advantage of this observation, and demonstrates a procedure for back-calculating the equivalent sand-grain roughness height k_s that would result in the *measured* powering penalty, i.e. the penalty determined from onboard-monitored vessel performance data. In short, this is achieved by iteratively running the Granville method until its *estimated* penalty matches the *measured* penalty within a given tolerance. The Granville method is thus preferred, since an alternative CFD approach would be prohibitively expensive for such an iterative approach. The only missing link is then the shape of $\Delta U^+ = \Delta U^+(k_s^+)$. To solve this, a suitable roughness function must be selected, where the function given in Demirel, Turan and Incecik (2017) seems to satisfactorily represent fouled surfaces, as shown above in Figure 4 (Schultz and Swain, 1999; Schultz, 2000, 2004, 2007; Schultz *et al.*, 2015).

On-board collected data includes variables of relevance for evaluating hull and propeller performance at a given point in time, most importantly speed through water and shaft power. The latter corresponds to the total power delivered to the propeller shaft(s), as determined from measured torque and shaft revolutions. Secondary variables, such as wind speed and vessel loading conditions (draft and trim), are important for filtering and establishing adequate power-speed baselines, against which performance is compared. All these variables are sampled at periods of less than a minute, in auto-logged data, or averaged in 24 hours, in noon reports compiled by the ship's crew (ISO, 2016).

Resistance penalties discussed in Chapter 3 (and in Paper II) may be added to the towing resistance of the ship, i.e. R_T . This resistance is obtained as output from Granville or CFD resistance methods, which however does not apply for self-propelled ships, due to changes in flow around the hull when propellers are operating in its wake. Thus, since towing resistance R_T cannot be directly measured onboard in-service ships, Granville- or CFD-derived resistance must be translated into shaft power P , using vessel speed U_{STW} and an adequate propulsive coefficient η_D :

$$P = R_T \times U_{STW} / \eta_D \quad (5)$$

The latter propulsive coefficient η_D is the product of open-water propeller efficiency, rotative efficiency and hull efficiency (Svensen, 1983; ITTC, 2014). Thus, at a constant ship speed through water U_{STW} and assuming a constant propulsive coefficient η_D (please refer to further discussion on this assumption in sub-section 4.5.2 of the Methodology), the difference in shaft power ΔP between a rough and a smooth hull will correspond to a given difference in towing resistance ΔR_T , which in the case of Paper V is modelled using the Granville method (Schultz, 2007), multiplied by U_{STW} / η_D .

Paper V further demonstrates that currently-adopted in-service performance values, such as percentage speed loss (ISO, 2016), are tied to the type of vessel, as well as being dependent on vessel speed. These dependencies hinder a comparison between vessels in terms of hull and propeller performance, and introduce uncertainty in performance results for a vessel with varying operational speed and loading condition. Thus, a novel performance indicator based on the concept of equivalent sand-grain roughness aims at providing an absolute measure of hull (and propeller) performance, which is demonstrated to yield qualitative agreement with diving reports on hull fouling, and would justify the investment in computation time (about one second per data point, on a laptop computer). Assumptions and limitations of Paper V's approach are further discussed in the next sub-section, on Methodology.

4.5. Methodology

In the context of available literature, the present sub-section further discusses currently adopted methodology for each of the main parts of this thesis, namely: (1) adhesion strength and cleaning forces, and (2) hull roughness penalties and limitations of vessel performance analysis in regard to biosecurity.

4.5.1. Adhesion strength and cleaning forces

Matching of in-water cleaning forces with adhesion strength of fouling organisms is suggested as an approach to minimize damage or wear on hull coatings (Paper I). However, methodological issues should be discussed, in order to pinpoint the practical value and limitations of methods used in Paper I, III and IV.

Regarding macrofouling, the occurrence of cohesive failure (shell breakage) on certain coatings, namely those coatings with limited or no foul-release properties, suggests that in-water cleaning should be avoided on such coatings when these are colonized by macrofouling (Paper I). Also, most of previous literature reviewed in Paper I, which uses the handheld force-gauge method, failed to report the share of void readings, i.e. the percentage of readings that were excluded due to >10% of the organism's shell remaining adhered (ASTM D5618, 1994). Such reporting is not normative under the current standard. The unreported share represents a methodological issue, considering that mean adhesion strength values for populations with extensive cohesive failure will be underestimated, due to the fact that only the shells that did *not* break are represented in the mean value. Therefore, in a future revision of the standard (ASTM D5618, 1994), reporting of cohesive failure should be made normative, as already practiced by some (Webster, Pieper and Nasrullah, 2010; Yebra and Català, 2011).

Regarding microfouling, other challenges must be discussed, namely the ephemeral properties of this type of fouling, accuracy of adhesion strength values from waterjet testing and, finally, the usefulness of adhesion strength values in calibrating full-scale in-water cleaning devices.

The ephemeral properties of microfouling had already been noted in earlier studies (Swain and Schultz, 1996; Hunsucker and Swain, 2016). In those studies, comparisons between coatings were restricted to the same date and deployment site, and no comparisons could be performed between different dates, due to temporal variations in microfouling communities. Aging of the coating adds to the

temporal variability, meaning that any adhesion strength value measured on a given coating at a given point in time can only be generalized as an approximate value for that combination of type of coating, coating age and type of fouling.

Additionally, it has been found that adhesive properties of biofilms depend on the hydrodynamic conditions under which these are grown (Finlay *et al.*, 2013; Zargiel and Swain, 2014). In Paper IV, adhesion strength was tested on statically-immersed coatings, which would therefore be expected to be removed at lower cleaning forces than microfouling developed on active hulls.

Since the above factors of date, coating age, deployment site and hydrodynamic conditions all contribute to variability in adhesion strength results, the values presented in Paper IV for statically-immersed AF and FR coatings should not be generalized for all active vessels. These adhesion strength values should instead be used as approximate minimal required forces for in-water cleaning of reported types of fouling, and not as prescriptive values. Regarding the types of fouling, these were evaluated in Paper IV using the US Navy fouling rating (Naval Sea Systems Command, 2006), which classifies microfouling into only two levels: incipient slime (Fouling Rating 10), corresponding to biofilm with a visible underlying surface, and advanced slime (Fouling Rating 20), corresponding to a thicker biofilm that obscures the underlying surface (Table 3 of Paper IV). This rating carries no quantitative information on biofilm composition and abundance. However, it is here argued that a taxonomic and abundance approach, as followed in other studies (Zargiel and Swain, 2014; Hunsucker and Swain, 2016), would be of reduced applicability for a diving or hull cleaning company in face of a microfouled hull, since these professionals have no resources to carry out such detailed taxonomic and abundance studies before each cleaning. Any data on taxonomic and abundance is therefore arguably more relevant for the development of new coatings, than it is as a practical approach of selecting forces for in-water cleaning. Finally, while these issues limit a more accurate calibration of cleaning devices, they also put less requirements in terms of accuracy for determining adhesion strength values, as discussed next.

The determination of microfouling adhesion strength using immersed waterjet testing, as discussed under Paper III and implemented in Paper IV, while representing an improvement from previous water-in-air jets, still suffers from some uncertainties, such as: the validity of applying progressively increasing forces in adhesion testing, discrepancies between numerical and experimental

semi-empirical formulas for wall shear stress, and unquantified time-dependent effects.

The testing of microfouling adhesion strength with progressively increasing forces, until a visually-clean surface is obtained or the highest achievable force is reached, was originally intended for comparisons between different foul-release products (Swain and Schultz, 1996; Hunsucker and Swain, 2016). Therefore, it cannot be stated that translating a waterjet only once over the surface, using the highest hydrodynamic force, would be equivalent to translating the waterjet several times, each time with increasing force, as used in adhesion testing. Indeed, some parts of the biofilm are removed at lower forces, while the most tenacious are only removed at higher forces (if at all removed). In other words, it remains to be proven that the highest tested forces would, in one pass of the waterjet, lead to the intended result, i.e. a visually clean surface. Paper IV thus recommends further full-scale testing on representative patches of fouling on the hull, before selecting cleaning parameters. However, this limitation does not affect the testing of hypothesis of negligible coating damage and wear during cleaning at adhesion-strength level, as discussed further below.

In Paper IV, semi-empirical formulas for wall forces under immersed waterjets, as determined in Paper III, are applied in quantifying forces exerted under adhesion-strength testing. However, as pointed out in Paper III, there is still considerable discrepancy between semi-empirical formulas derived from original CFD simulations and those formulas derived from reference experimental and numerical studies (Table 4 in Paper III). This means that further refinement of the CFD method presented in Paper III must be pursued, namely by looking into inlet flow conditions, nozzle-shape details and turbulence modelling, and also further experimental measurements are required on immersed waterjet adhesion testing devices, using pressure taps for measuring stagnation pressure, and hot-film sensors or electrochemical methods for wall shear stress. In the absence of this data, and to be conservative, Paper IV made use of semi-empirical formulas derived in Paper III from previous experimental and numerical studies (Table 4 in Paper III: slopes derived from reference studies).

In order to match in-water cleaning forces to the adhesion strength of microfouling, above-mentioned CFD and experimental methods used for determining wall forces under impinging jets would also need to be applied in testing of existing commercial waterjet cleaning devices. Thus, calibration would be made possible, e.g. by deriving relations between parameters that are easy to

control and monitor (e.g. nozzle diameter and seawater pressure at the nozzle) and forces exerted on the wall, which would be determined using either an experimental or a numerical approach. Still, as discussed above in this subsection, several factors may influence the reference values of adhesion strength, not least the so-far unquantified dependencies of required forces on the nozzle translation speed, especially for high-speed rotating waterjets, as mentioned in Papers III and IV. Therefore, considering these unknowns and the width of uncertainties in Figure 6 of Paper IV (before settlement of tenacious biofilms and reaching the highest allowed forces in the immersed waterjet test setup), the tolerance at which to follow recommended cleaning forces of Paper IV is arguably in the range of one order of magnitude.

Finally, for determining the effects of cleaning on the wear of an AF coating in Paper IV, a biocide release rate method was used, which was based on the polishing rate mass balance. This method is adequate for coatings that undergo ablation, such as self-polishing coatings (Finnie, 2006).

The polishing rate mass-balance method relies on measuring a change in thickness of the coating and then accounting for the amount of biocide that was contained in the removed layer. This method has been shown to be within the uncertainty of stabilized biocide release rates, measured using chemical analysis of in-situ leaching (Tribou and Swain, 2017). However, in the presence of a leached layer (Howell and Behrends, 2006), the total biocide release will be underestimated, since copper and other biocides are released also from *within* the layers of coating that are *not* removed by polishing or wear. Therefore, to assess the importance of this underestimation, SEM-EDX imaging was performed on cross-sections of newly painted, cleaned and non-cleaned samples of the AF coating. In all these cases, except for the newly-painted AF, the thickness of the leached layer (Figure 8 in Paper IV) was observed to be comparable to that of the polished layer (Figure 7 in Paper IV). This indicates that the polishing rate mass-balance method may not be adequate for environmental risk assessment, as it considerably underestimates the total release of biocides, and therefore other methods should be used for that purpose (e.g. see Lagerström, 2019). However, for the current purpose of comparing different cleaning treatments (bi-monthly versus monthly cleanings), the polishing rate mass-balance method did not indicate any significant increase in polishing-based release rate due to cleaning, within the current uncertainties. Since the latter uncertainties are still large, $\sim 2\text{-}4 \mu\text{g Cu} / \text{cm}^2 / \text{day}$ compared to a measured biocide release rate of $\sim 13 \mu\text{g Cu} / \text{cm}^2 / \text{day}$ (Figure 7 in Paper IV), other possibly

more-accurate methods should be tested in the future, such as portable XRF, i.e. energy dispersive X-ray fluorescence spectroscopy (Lagerström *et al.*, 2018). Also, such cleaning schemes should be extended in time, from one to several years, as differences between cleaning frequencies may be only detectable after a few years' time (Tribou and Swain, 2017).

4.5.2. Hull roughness penalties and biosecurity

In this second part of the methodology, several aspects related to modelling of hull roughness penalties (Paper II) and evaluating in-service vessel performance (Paper V) are discussed, namely: the accuracy of CFD as a reference, challenges in vessel performance data, decoupling of propeller roughness from hull roughness effects, uncertainties and adequacy of ship physical models and roughness functions, and finally the limitations of using vessel performance in biosecurity risk assessment.

In evaluating the merits of different hull roughness modelling approaches (Paper II), it was implicitly assumed that current CFD methods yield the most accurate results, as methods were ranked according to how close these matched CFD results on the KRISO containership hull. The rationale behind this was that CFD hull simulations include three-dimensional effects, whereas flat plate methods do not. However, while *smooth* hull resistance has been validated against extrapolated model-scale experimental results to within <5% (Demirel, Turan and Incecik, 2017; Song, Demirel and Atlar, 2019), validation has not yet been performed for *rough* hull conditions. Thus, in order to determine the accuracy of CFD rough-hull results, full-scale trial data would be required on a hull with fully-characterized surfaces, i.e. known roughness function $\Delta U^+ = \Delta U^+(k_s^+)$ and equivalent sand-grain roughness height k_s . The latter hydraulic data would either represent the entire hull surface, which might be difficult to achieve in practice due to non-uniformities in roughness across the hull, or else rely on sampling of separate zones on the hull, which would require that such non-uniform distribution of roughness parameters be also considered in the CFD model under validation. To the best available knowledge, such complete hydraulic characterization of an entire hull has not been attempted yet, though some promising techniques, such as hull-mounted probes, silicone imprints and 3D printing, may enable this (Hutchins *et al.*, 2016; Monty *et al.*, 2016).

Since the gap between roughness profile measurements (e.g. height and surface topography) and their hydrodynamic effects is not yet entirely bridged

(Barros, Schultz and Flack, 2018; Speranza *et al.*, 2019), an approach is presented in Paper V based on in-service vessel performance data. The latter data is thus used in deriving the hydraulic roughness height that would represent a given powering penalty, effectively using the ship as a hydrodynamic test facility. However, vessel performance data is not without its challenges, namely sensor bias and drift, sensor failure, unavailable measurements (e.g. thrust) and uncertainties or inadequacy of physical modelling of the ship.

As noted in Paper V, sensor data collected onboard vessels could be made more reliable, e.g. by more frequent maintenance and sensor recalibrations. An illustrative example is that of vessel speed through water, which is one of the two primary variables for evaluating vessel performance, together with shaft power. Speed through water data were unreliable for all of three vessels studied, exhibiting considerable drift, as well as precision issues in two of the vessels (B and C). Consequently, speed over ground was used as a proxy, which includes effects of ocean currents. An ocean current of just 1-2 knots is enough to considerably affect the accuracy of performance values, representing an absolute speed difference of 7-14% for vessel A and 4-9% for vessels B and C (percentage of design speed values given in Table 1 of Paper V). Therefore, it is not surprising that results include a considerable level of noise, considering that ocean currents will indiscriminately follow or oppose the ship's movement at any given point in time. Finally, some variables are typically not measured, such as propeller thrust. The latter would enable to decouple propeller roughness effects on powering from those of hull roughness. As it stands, any of the discussed performance indicators in Paper V still represents the *combined* performance of hull and propeller (ISO, 2016). This combined performance means that the reported equivalent sand-grain roughness height values represent the penalties associated with hull and propeller roughness by an equivalent flat-plate resistance penalty, which is translated into propulsion power by a *smooth* propeller, leading to overestimation of hull roughness due to inclusion of propeller roughness-related frictional losses. Although the approach of a smooth propeller does not exactly match reality, i.e. propellers are also subject to fouling and diver-operated polishing events (Munk, Kane and Yebra, 2009), it does indicate that more detailed on-board measurements and more refined physical models are needed for sub-metering these effects, i.e. separating hull roughness from propeller roughness.

Uncertainties and adequacy of physical modelling of a ship are of utmost importance, since these affect baselines, i.e. the expected performance against which comparisons are drawn. Currently, uncertainties in extrapolated results

from model-scale tests on the hulls of Paper V were not available. Additionally, interpolation of baselines in regard to changes in vessel draft and trim introduces further errors. Also, the uniqueness of vessels, due to uncertainties related to the ship's construction, may affect the adequacy of the physical model of a ship (Paereli and Krapp, 2017; Tillig *et al.*, 2018). Although these uncertainties are currently not dealt with in further detail, these factors should be born in mind when interpreting the results. Finally, as discussed in Paper V in more detail, towing-tank resistance results include correlation coefficients that already add hull roughness effects. These effects were currently subtracted, assuming that the standard procedure was followed by the towing tanks, i.e. using a roughness allowance based on Townsin's formula with peak-to-valley roughness height of 150 μm (ITTC, 2014). The above uncertainties increase the precision errors and bias in the results of Paper V, inclusively leading to *negative penalties*, which would mean that the hull is performing *better* than the ideally-smooth hull. As a limitation to the calculation of equivalent sand-grain roughness modelling proposed in Paper V, such negative-penalty cases must be avoided as much as possible, by using median power penalties instead of all data points, due to the impossibility of modelling a negative penalty using a ΔU^+ function that is always non-negative.

Another aspect related to the adequacy of physical modelling corresponds to the assumption made in Paper V that the propulsive coefficient η_D is not affected by hull roughness. The propulsive coefficient η_D is the product of open-water propeller efficiency, hull efficiency and rotative efficiency. Thus, while some authors previously defended that η_D should *decrease* with increasing hull roughness, due to an increase in propeller thrust at a given vessel speed leading to decreased open-water efficiency (Schultz, 2007), other authors pointed out that hull roughness has a reverse effect on hull efficiency, which would *increase* due to a thicker boundary layer at the propeller plane (Munk, Kane and Yebra, 2009). However, a more detailed analysis performed by Svensen (1983, pp. 49–61) had demonstrated that the hull-roughness effect on open-water efficiency is almost exactly cancelled out by the effect on hull efficiency, resulting in a minimal change in propulsive coefficient η_D . Therefore, the approximation made in Equation 4 of Paper V is justified, according to which propulsive coefficient for the rough hull condition can be approximated by the smooth-hull propulsive coefficient at a given vessel speed, as obtained from self-propulsion tests. In practical terms, this means that a percentage increase in resistance is assumed to be numerically equal to a percentage increase in power. Such hypothesis

should be further tested for specific vessel cases, e.g. using self-propulsion CFD simulations (Castro, Carrica and Stern, 2011; Song, Demirel and Atlar, 2019).

A final modelling assumption deals with the selection of a roughness function $\Delta U^+ = \Delta U^+(k_s^+)$ in Paper V. Demirel et al.'s roughness function was selected (Demirel, Turan and Incecik, 2017), considering that it follows the inflectional behaviour of roughness function results for different types of fouled surfaces (Figure 4 in sub-section 3.3). In Figure 4, it can be observed that, by instead choosing a Colebrook-type function, lower values of k_s would be obtained in the transitionally-rough regime. Although the latter approach would probably represent better the behaviour of clean AF and FR coatings (as indicated by most of the studies reviewed under sub-section 3.3), it is currently argued that the shape of the roughness function should be as widely applicable as possible, to include biofouling. Also, it is clear that, for any meaningful comparison between vessels, the same roughness function should be used throughout. Finally, the only impediment to applying the method as described in Paper V would be non-monotonicity of the roughness function, where the ΔU^+ may be ambiguous, i.e. same ΔU^+ value obtained at different k_s values (Grigson, 1987). This non-monotonicity would give rise to multiple possible solutions for k_s , from which only one k_s value should be selected based on other criteria, e.g. based on trends in k_s from previous data points. However, a monotonic increase in ΔU^+ with k_s^+ seems to be the most common behaviour in recent studies on relevant hull roughness conditions (Figure 4 in sub-section 3.3).

Maintenance approaches are typically sorted into three categories (see Raptodimos *et al.*, 2015): **corrective maintenance**, e.g. reactive in-water hull cleaning on macrofouling; **preventive maintenance**, e.g. frequent and gentle wiping of the hull (hull grooming) regardless of monitored vessel performance; and **predictive maintenance**, e.g. using maintenance triggers based on hull-and-propeller performance monitoring (condition-based maintenance). From Paper V, as long as vessel performance suffers from high uncertainties, currently as high as ± 3 percentage points in speed loss from noon reports (95% confidence intervals for averaging period of 3 month, Paper V – Table 3), early detection of relatively small changes in performance will be challenging, e.g. microfouling that leads to ~ 3 -4% speed loss. Thus, relying exclusively on vessel performance as a trigger for in-water maintenance, i.e. following a predictive condition-based approach, might lead to delayed intervention (Armstrong and Banks, 2015), reaching the point when macrofouling has already established on both main and niche areas of the hull (~ 6 -12% speed loss). For auto-logged data, confidence

intervals are narrower, below ± 1 percentage point for speed loss (Paper V – Table 3, vessels B-C), and may thus enable triggers in a condition-based approach to maintenance. Otherwise, planned in-water maintenance, following a preventive-maintenance approach supported by historical data from previous drydocking intervals, might still prove adequate in implementing in-water hull grooming. Such approach seems particularly suited for ships with fixed routes and schedules.

Finally, from a biosecurity perspective, it is not enough to consider vessel performance in evaluating a hull maintenance approach. Niche areas, which are typically sheltered from hydrodynamic forces, may have minimal impact on vessel fuel performance, and therefore receive less attention from shipowners, except in locations where fouling might lead to measurable operational losses (e.g. sea chests and intakes for cooling water). However, such niche areas pose an important biosecurity risk, due to typically higher species diversity and fouling abundance compared to other areas exposed to higher hydrodynamic forces (Davidson, Brown, Mark D. Sytsma, *et al.*, 2009; Moser *et al.*, 2017). Additionally, such niche areas may be difficult to access by in-water cleaning devices, leading to lower cleaning efficacy and thus requiring manual cleaning by divers (Morrissey and Woods, 2015). This issue has been identified as a gap between industry and biosecurity perspectives (Davidson *et al.*, 2016; Zabin *et al.*, 2018). Closing of this gap will probably require increasing regulatory requirements, which would be enforced by risk-based inspections with ROVs or divers (Zabin *et al.*, 2018). Such regulatory pressure would promote the development and wider application of technical solutions for niche areas, such as the use of specifically-developed coating products for those areas, different from those applied on other parts of the hull (Davidson *et al.*, 2016) and preferably minimizing the total release of biocides.

4.6. Future research and development

Considering the topics discussed in this thesis and the remaining knowledge gaps, an outlook on future research and development is given in this sub-section.

In order to effectively match in-water cleaning forces on commercial in-water cleaning devices to the adhesion strength of fouling, further research is required on the following aspects:

- Refining CFD models of waterjet cleaning, to include effects such as tilted nozzles (impingement angle $< 90^\circ$), nozzle design, curved hull

surfaces, multi-jet setups and fast-translating or rotating nozzles. Further validation of turbulence models and boundary conditions is also required, in order to solve existing gaps between experimental and numerical results.

- As an alternative to comprehensive CFD studies on existing in-water cleaning devices, experimental measurements should be performed on the wall forces exerted by commercial waterjet systems, e.g. using hot-film sensors and pressure taps, aiming at the calibration of such systems against adhesion strength data.
- Expanding the amount and accuracy of adhesion strength data on microfouling, using immersed waterjet testing. In such studies, higher nozzle translation speeds should be tested, in the range of values relevant for commercial cleaning devices (> 1 m/s). Furthermore, research is needed on practical ways for determining the abundance and composition of marine slimes, e.g. using fluorescence methods (Fischer, Wahl and Friedrichs, 2013).
- Finally, adhesion testing is needed on panels that have been exposed to flow conditions similar to active hulls (dynamic exposure).

Other outstanding issues related to in-water cleaning also require further research and development, namely:

- The efficacy of waste containment technology, which should consider both amount and rate of survival of uncaptured biological waste.
- Efficacy of cleaning methods on different areas of the hull, namely niche areas and close to the waterline.
- Investigation of alternatives for niche areas on the hull, giving preference to non-biocidal approaches.

Tools for monitoring of vessel performance would benefit from further research and development on the following aspects:

- Increasing the effectiveness of any existing schemes for on-board sensor testing, calibration and maintenance, to decrease the likelihood of sensor drift and failure.
- Implementation and testing of on-board thrust measurements, as well as development of physical models to separate hull roughness effects from propeller roughness.

- Uncertainty analysis for physical modelling of in-service ships, in order to identify the origin and importance of any discrepancies between modelled and measured out-of-dock performance.
- Full-scale trials on hulls with fully-characterized surface roughness, where the latter characterization should rely on experimental measurements of hydraulic parameters, rather than solely on surface topography or peak-to-valley roughness height measurements. Results from such trials would enable direct validation of CFD and other methods used in modelling roughness at the ship scale. However, the accuracy of smooth-hull CFD results in full scale may compromise such validation, unless a series of cases with varying roughness can be studied for the same hull.
- Further testing of the effects of hull roughness on the propulsive coefficient (propeller-hull interactions), e.g. using CFD self-propulsion simulations at the ship scale.

Finally, on a transversal approach, further research is needed on policy tools that would lead to the adoption of best practices in terms of hull management, which might need to be tailored for each shipping segment or even for specific routes. Therefore, research is needed on the pros and cons of different measures, which might include discounts on port and fairway fees for lightly-fouled vessels, complementing e.g. the existing ranking based on type of antifouling paint within the Clean Shipping Index (CSI, 2018), or levies and access restrictions for ships that do not follow best practices or exhibit moderate-to heavily-fouled hulls, with special attention to niche areas. Also, cost-effective enforcement and inspection approaches should be further investigated, namely following a risk-based approach (Zabin *et al.*, 2018).

5. Conclusions

*Whatsoever is, is but as it were the seed of that
which shall be.*

Marcus Aurelius Antoninus
(121-180 AD, *in Meditations* 4.29)

The importance of shipping to human development is undeniable, as it provides economical and efficient transport of raw materials and products across the globe, besides generally contributing to global peace and stability through trade (Stopford, 2009). However, its impacts are, for the most part, kept away from the public's eye and mind, while requiring continuous work in policymaking, on the one hand, and research and technology development, on the other hand.

Biofouling on ship's underwater surfaces has been an issue for millennia. Today, with ever-increasing transport by sea, the relevance of biofouling issues has not decreased, in spite of considerable advances in technology used in preventing it. Pressing issues are identified as: hull roughness penalties leading to increased fuel consumption and emissions of greenhouse gases and air pollutants, as well as the risk of spread of non-indigenous species (NIS) via hull fouling, and chemical pollution from fouling-control paint components.

The current thesis represents a step in improving existing approaches to manage marine fouling. More specifically, methods were discussed both for testing the adhesion strength of biofouling on ship hull coatings, as well as for quantifying the effects of maintenance on ship fuel performance, thus providing tools for improving hull fouling management. The current outcome supports a preventive approach to hull maintenance, such as hull grooming (gentle, frequent hull wiping). Alternatively, a predictive approach based on vessel performance and condition monitoring would target early fouling.

In terms of level of in-water cleaning forces required to remove marine growth, an approach is suggested for matching in-water cleaning forces to the adhesion strength of marine fouling. Preference should be given to targeting of early stages of fouling, i.e. microfouling or marine slime, instead of allowing the development

of more-advanced forms of fouling, i.e. macrofouling such as barnacles and other types of hard fouling. For microfouling, wall shear stress values in the order of 1 kPa seem to be adequate for minimizing the amount of slime developed on most-common hull coating types, whilst resulting in negligible wear and release of paint component to the marine environment. Directions for further research and development are identified in this area, namely refinement of numerical simulation models of waterjet cleaning, need for full-scale measurements on existing in-water cleaning devices, and improving both availability and accuracy of adhesion-strength data.

Regarding tools for evaluating maintenance approaches from a vessel-performance perspective, a new indicator is proposed and demonstrated, which is based on the concept of equivalent sand-grain roughness height. Such approach relies on modelling of roughness effects at the ship scale, effectively using in-service vessels as hydrodynamic testing facilities. Possible improvements to both physical modelling of ship resistance and powering, on the one hand, and the quality and quantity of on-board data, on the other hand, were evaluated and discussed, namely corrections for hull form effects in physical models, and increased monitoring and maintenance of on-board sensors. Flat-plate models of roughness penalties at the ship scale, namely the Granville method, are shown to yield reasonably accurate results, comparable to other more-detailed CFD simulations on hull roughness penalties. However, further experimental testing at both lab and full scale will be required in order to quantify the errors associated with these numerical approaches.

From a biosecurity perspective, further work is needed on testing of biofouling waste containment on in-water cleaning devices, as well as the efficacy of different prevention methods in reducing the risks of NIS transport via hull fouling. Several initiatives have taken up this issue, such as IMO's GloFouling, and it is hoped that these may bring about effective change in today's practices all over the globe.

As usual, there are no one-size-fits-all solutions in shipping. Shipowners, shipping companies, policymakers, researchers and entrepreneurs will know best how the tools discussed in here apply to their specific cases. It is hoped that current results may inspire ever better tailored and more elegant solutions, and that future ships will contribute less to chemical pollution of marine environments, exhibit less fouling on their hulls, and emit less greenhouse gases and air pollutants. As former US-President Barack Obama once said, "Better is good". However, one should ask, for how long?

References

- Allen, M. R. *et al.* (2018) *Global Warming of 1.5°C. An IPCC Special Report on the impacts of global warming of 1.5°C above pre-industrial levels and related global greenhouse gas emission pathways, in the context of strengthening the global response to the threat of climate change*,. In Press. Edited by V. Masson-Delmotte *et al.* IPCC. Available at: <https://www.ipcc.ch/sr15/>.
- Anil, A. C. *et al.* (2010) 'Larval development, sensory mechanisms and physiological adaptations in acorn barnacles with special reference to *Balanus amphitrite*', *Journal of Experimental Marine Biology and Ecology*. Elsevier B.V., 392(1–2), pp. 89–98. doi: 10.1016/j.jembe.2010.04.012.
- Armstrong, V. N. and Banks, C. (2015) 'Integrated approach to vessel energy efficiency', *Ocean Engineering*, 110, pp. 39–48. doi: 10.1016/j.oceaneng.2015.10.024.
- ASTM D5618 (1994) *Measurement of Barnacle Adhesion Strength in Shear (Reapproved 2011), Standard Test Method*. West Conshohocken, PA, United States.
- Atalah, J. *et al.* (2016) 'It's a wrap: encapsulation as a management tool for marine biofouling', *Biofouling*, 32(3), pp. 277–286. doi: 10.1080/08927014.2015.1137288.
- Australian Government (2013) 'Anti-fouling and in-water cleaning guidelines', June, p. 26.
- Barros, J. M., Schultz, M. P. and Flack, K. A. (2018) 'Measurements of skin-friction of systematically generated surface roughness', *International Journal of Heat and Fluid Flow*. Elsevier, 72(January), pp. 1–7. doi: 10.1016/j.ijheatfluidflow.2018.04.015.
- Bebić, D. *et al.* (2018) 'EDD – Economic Benefit Analysis of Extending Dry Docking Interval', *Transactions on Maritime Science*, 7(02), pp. 164–173. doi: 10.7225/toms.v07.n02.006.
- Bell, A. *et al.* (2011) *Risk Analysis: Vessel Biofouling*. Wellington (New Zealand). Available at: <https://www.mpi.govt.nz/dmsdocument/2863>.
- Beltaos, S. and Rajaratnam, N. (1974) 'Impinging circular turbulent jets', *ASCE Journal of the Hydraulics Division*, 100(10), pp. 1313–1328.
- Berglin, M. *et al.* (2001) 'The adhesion of the barnacle *Balanus improvisus*, to poly(dimethylsiloxane) fouling-release coatings and poly(methyl methacrylate) panels: The effect of barnacle size on strength and failure mode', *Journal of Adhesion Science and Technology*, 15(12), pp. 1485–1502. doi: 10.1163/156856101753213321.
- Bergman, K. and Ziegler, F. (2018) 'Environmental impacts of alternative antifouling methods and use patterns of leisure boat owners', *The International Journal of Life Cycle Assessment*. The International Journal of Life Cycle Assessment, pp. 1–10. doi: <https://doi.org/10.1007/s11367-018-1525-x>.
- BIMCO (2013) *Hull fouling clause for time charter parties (updated 16 July 2015), Special Circular No. 3*. Available at: <https://www.bimco.org/contracts-and-clauses/bimco-clauses> (Accessed: 8 May 2017).

Blanco-Davis, E., del Castillo, F. and Zhou, P. (2014) 'Fouling release coating application as an environmentally efficient retrofit: a case study of a ferry-type ship', *The International Journal of Life Cycle Assessment*, 19(10), pp. 1705–1715. doi: 10.1007/s11367-014-0780-8.

Bradshaw, P. (2000) 'A note on "critical roughness height" and "transitional roughness"', *Physics of Fluids*, 12(6), p. 1611. doi: 10.1063/1.870410.

BRS (2019) *Shipping and Shipbuilding Markets: Annual Review*. Neuilly-sur-Seine, France. Available at: <https://www.brsbrokers.com/annualreview2019.html>.

Cahill, P. *et al.* (2019) 'A portable thermal system for reactive treatment of biofouled internal pipework on recreational vessels', *Marine Pollution Bulletin*. Elsevier, 139(December 2018), pp. 65–73. doi: 10.1016/j.marpolbul.2018.12.032.

Cal, R. B. *et al.* (2009) 'The rough favourable pressure gradient turbulent boundary layer', *Journal of Fluid Mechanics*, 641, p. 129. doi: 10.1017/S0022112009991352.

California State Lands Commission (2017) *Biofouling Management to Minimize the Transfer of Nonindigenous Species from Vessels Arriving at California Ports*, *Barclays Official California Code of Regulations*. Available at: [https://govt.westlaw.com/calregs/Document/IC9FA65EBE3EC45289FC54C496DE5E009?originationContext=document&transitionType=StatuteNavigator&needToInjectTerms=False&viewType=FullText&t_T2=2298&t_S1=CA ADC s&contextData=\(sc.Default\)](https://govt.westlaw.com/calregs/Document/IC9FA65EBE3EC45289FC54C496DE5E009?originationContext=document&transitionType=StatuteNavigator&needToInjectTerms=False&viewType=FullText&t_T2=2298&t_S1=CA ADC s&contextData=(sc.Default)) (Accessed: 18 July 2019).

Callow, J.A. and Callow, M. E. (2006) 'The Ulva Spore Adhesive System', in Smith, A. M. and Callow, James A. (eds) *Biological Adhesives*. Berlin: Springer-Verlag, pp. 63–78.

Candries, M. *et al.* (2003) 'The measurement of the drag characteristics of tin-free self-polishing co-polymers and fouling release coatings using a rotor apparatus.', *Biofouling*, 19 Suppl(September 2015), pp. 27–36. doi: 10.1080/0892701021000026138.

Cao, S. *et al.* (2011) 'Progress of marine biofouling and antifouling technologies', *Chinese Science Bulletin*, 56(7), pp. 598–612. doi: 10.1007/s11434-010-4158-4.

Cassé, F. *et al.* (2007) 'Laboratory screening of coating libraries for algal adhesion.', *Biofouling*, 23(3–4), pp. 267–276. doi: 10.1080/08927010701288336.

Castro, A. M., Carrica, P. M. and Stern, F. (2011) 'Full scale self-propulsion computations using discretized propeller for the KRISO container ship KCS', *Computers and Fluids*. Elsevier Ltd, 51(1), pp. 35–47. doi: 10.1016/j.compfluid.2011.07.005.

Cebeci, T. and Bradshaw, P. (1977) *Momentum transfer in boundary layers*. New York: Hemisphere Publishing Corporation / McGraw-Hill Book Company.

Champ, M. A. (2000) 'A review of organotin regulatory strategies, pending actions, related costs and benefits', *Science of the Total Environment*, 258(1–2), pp. 21–71. doi: 10.1016/S0048-9697(00)00506-4.

Chiovitti, A., Dugdale, T. M. and Wetherbee, R. (2006) 'Diatom Adhesives: Molecular and Mechanical', in Smith, A. M. and Callow, J. A. (eds) *Biological Adhesives*. Berlin: Springer-Verlag.

Crisp, D. . *et al.* (1985) 'Adhesion and substrate choice in mussels and barnacles', *Journal of Colloid and Interface Science*, 104(1), pp. 40–50. doi: 10.1016/0021-9797(85)90007-4.

CSI (2018) *Clean Shipping Index - Methodology and Reporting Guidelines*. Available at: <https://www.cleanshippingindex.com/wp-content/uploads/2019/04/2018-10-26-Methodology-and-Reporting-Guidelines.pdf> (Accessed: 26 July 2019).

Davidson, I. C., Brown, C. W., Sytsma, Mark D, *et al.* (2009) 'The role of containerships as transfer mechanisms of marine biofouling species.', *Biofouling*, 25(7), pp. 645–655. doi: 10.1080/08927010903046268.

Davidson, I. C., Brown, C. W., Sytsma, Mark D., *et al.* (2009) 'The role of containerships as transfer mechanisms of marine biofouling species.', *Biofouling*, 25(7), pp. 645–655. doi: 10.1080/08927010903046268.

Davidson, I. C. *et al.* (2016) 'Mini-review: Assessing the drivers of ship biofouling management – aligning industry and biosecurity goals', *Biofouling*, 32(4), pp. 411–428. doi: 10.1080/08927014.2016.1149572.

Demirel, Y. K. *et al.* (2015) 'Experimental Determination of the Roughness Functions of Marine Coatings', *SCC2015: Shipping in Changing Climates Conference 2015*, (FoulXSpel 1).

Demirel, Y. K., Turan, O. and Incecik, A. (2017) 'Predicting the effect of biofouling on ship resistance using CFD', *Applied Ocean Research*. Elsevier B.V., 62, pp. 100–118. doi: 10.1016/j.apor.2016.12.003.

Drake, J. M. and Lodge, D. M. (2007) 'Hull fouling is a risk factor for intercontinental species exchange in aquatic ecosystems', *Aquatic Invasions*, 2(2), pp. 121–131. doi: 10.3391/ai.2007.2.2.7.

DRYDOCK Magazine (2019) *Aquaterras hull coating for first cruise ship*. Available at: www.drydockmagazine.com/aquaterras-hull-coating-for-first-cruise-ship (Accessed: 30 July 2019).

Dürr, S. and Thomason, J. C. (2009) *Biofouling, Biofouling*. Edited by S. Drr and J. C. Thomason. Oxford, UK: Wiley-Blackwell.

Earley, P. J. *et al.* (2014) 'Life cycle contributions of copper from vessel painting and maintenance activities', *Biofouling*, 30(1), pp. 51–68. doi: 10.1080/08927014.2013.841891.

Fazey, I. *et al.* (2018) 'Ten essentials for action-oriented and second order energy transitions, transformations and climate change research', *Energy Research and Social Science*. Elsevier, 40(April 2017), pp. 54–70. doi: 10.1016/j.erss.2017.11.026.

Finlay, J. A. *et al.* (2002) 'Adhesion strength of settled spores of the green alga *Enteromorpha*', *Biofouling*, 18(4), pp. 251–256. doi: 10.1080/08927010290029010.

Finlay, J. A. *et al.* (2013) 'A novel biofilm channel for evaluating the adhesion of diatoms to non-biocidal coatings.', *Biofouling*, 29(January 2015), pp. 401–11. doi:

10.1080/08927014.2013.777046.

Finnie, A. A. (2006) 'Improved estimates of environmental copper release rates from antifouling products', *Biofouling*, 22(5), pp. 279–291. doi: 10.1080/08927010600898862.

Fischer, M., Wahl, M. and Friedrichs, G. (2013) 'Field sensor for in-situ detection of marine bacterial biofilms', *Sea Technology*, 54(2), pp. 49–52.

Flack, K. A. and Schultz, M. P. (2010) 'Review of Hydraulic Roughness Scales in the Fully Rough Regime', *Journal of Fluids Engineering*, 132(4), p. 041203. doi: 10.1115/1.4001492.

Flack, K. A. and Schultz, M. P. (2014) 'Roughness effects on wall-bounded turbulent flows', *Physics of Fluids*, 26(10), p. 101305. doi: 10.1063/1.4896280.

Flack, K. A., Schultz, M. P. and Rose, W. B. (2012) 'The onset of roughness effects in the transitionally rough regime', *International Journal of Heat and Fluid Flow*, 35, pp. 160–167. doi: 10.1016/j.ijheatfluidflow.2012.02.003.

Floerl, O. *et al.* (2005) *Efficacy of hull cleaning operations in containing biological material - I. Risk assessment. MAF Biosecurity New Zealand Project ZBS2002-04.*

Floerl, O. *et al.* (2009) 'The importance of transport hubs in stepping-stone invasions', *Journal of Applied Ecology*, 46(1), pp. 37–45. doi: 10.1111/j.1365-2664.2008.01540.x.

Freire-González, J. and Puig-Ventosa, I. (2015) 'Energy efficiency policies and the Jevons paradox', *International Journal of Energy Economics and Policy*, 5(1), pp. 69–79. Available at: <http://www.scopus.com/inward/record.url?eid=2-s2.0-84920986824&partnerID=tZOtx3y1>.

Grigson, C. (1987) 'Full-scale viscous drag of actual ship surfaces and the effect of quality of roughness on predicted power', *Journal of Ship Research*, 31(3), pp. 189–206.

Grigson, C. (1992) 'Drag losses of new ships caused by hull finish', *Journal of Ship Research*, 36(2), pp. 182–196.

Growcott, A., Kluza, D. and Georgiades, E. (2017) 'Review: In-water systems to reactively manage biofouling in sea chests and internal pipework', *Marine Technology Society Journal*, 51(2), pp. 89–104.

Halim, R. A. *et al.* (2018) 'Decarbonization pathways for international maritime transport: A model-based policy impact assessment', *Sustainability (Switzerland)*, 10(7). doi: 10.3390/su10072243.

Harzhauser, M. *et al.* (2019) 'A new Early Miocene barnacle lineage and the roots of sea-turtle fouling Chelonibiidae A new Early Miocene barnacle lineage and the roots of sea-turtle fouling', 2019. doi: 10.1080/14772019.2010.528053.

Hearin, J. *et al.* (2015) 'Analysis of long-term mechanical grooming on large-scale test panels coated with an antifouling and a fouling-release coating', *Biofouling*, 31(8), pp. 625–638. doi: 10.1080/08927014.2015.1081687.

Hearin, J. *et al.* (2016) 'Analysis of mechanical grooming at various frequencies on a large scale test panel coated with a fouling-release coating', *Biofouling*, 32(5), pp. 561–

569. doi: 10.1080/08927014.2015.1081687.

Holland, R. *et al.* (2004) 'Adhesion and motility of fouling diatoms on a silicone elastomer', *Biofouling*, 20(6), pp. 323–329. doi: 10.1080/08927010400029031.

Holm, E. R. (2012) 'Barnacles and biofouling', *Integrative and Comparative Biology*, 52(3), pp. 348–355. doi: 10.1093/icb/ics042.

Holm, E. R., Haslbeck, E. G. and Horinek, A. A. (2003) 'Evaluation of brushes for removal of fouling from fouling-release surfaces, using a hydraulic cleaning device.', *Biofouling*, 19(5), pp. 297–305. doi: 10.1080/0892701031000137512.

Howell, D. (2009) 'Testing the impact of biofilms on the performance of marine antifouling coatings', *Advances in Marine Antifouling Coatings and Technologies*, pp. 422–442. doi: 10.1533/9781845696313.2.422.

Howell, D. and Behrends, B. (2006) 'A methodology for evaluating biocide release rate, surface roughness and leach layer formation in a TBT-free, self-polishing antifouling coating', *Biofouling*, 22(5), pp. 303–315. doi: 10.1080/08927010600924304.

Hunsucker, K. Z. and Swain, G. W. (2016) 'In situ measurements of diatom adhesion to silicone-based ship hull coatings', *Journal of Applied Phycology*, 28(1), pp. 269–277. doi: 10.1007/s10811-015-0584-7.

Hutchins, N. *et al.* (2016) 'Turbulent boundary layers developing over rough surfaces: from the laboratory to full-scale systems', in *20th Australasian Fluid Mechanics Conference - December 2016*. Perth (AUS).

ICS (2017) *Shipping and World Trade*, International Chamber of Shipping Website. Available at: <http://www.ics-shipping.org/shipping-facts/shipping-and-world-trade> (Accessed: 6 May 2019).

IEA (2019) *Total Primary Energy Supply (TPES) by source: World 1990 - 2016*, Statistics data browser. Available at: <https://www.iea.org/statistics/balances> (Accessed: 19 August 2019).

IMO (2001) *International Convention On the Control of Harmful Anti-Fouling Systems on Ships*. London: The Stationery Office Limited.

IMO (2011) 'Guidelines for the control and management of ships' biofouling to minimize the transfer of invasive aquatic species', in *Resolution MEPC.207(62)*. London (UK), pp. 1–25.

IMO (2014) *Reduction of GHG emissions from ships - Third IMO GHG Study 2014 - Final Report*, MEPC 67/INF.3. Available at: [http://www.imo.org/en/OurWork/Environment/PollutionPrevention/AirPollution/Documents/Third Greenhouse Gas Study/GHG3 Executive Summary and Report.pdf](http://www.imo.org/en/OurWork/Environment/PollutionPrevention/AirPollution/Documents/Third%20Greenhouse%20Gas%20Study/GHG3%20Executive%20Summary%20and%20Report.pdf) (Accessed: 1 June 2017).

Inglis, G. J., Floerl, O. and Woods, C. M. C. (2012) *Scenarios of vessel biofouling risk and their management: an evaluation of options*, MAF Technical Paper No. 2012/07. Wellington (New Zealand).

ISO (2016) *ISO/DIS 19030: Ships and marine technology - Measurement of changes in hull and propeller performance [under development], TC 8 Ships and marine technology*. Available at: http://www.iso.org/iso/home/store/catalogue_tc/catalogue_detail.htm?csnumber=63774 (Accessed: 31 May 2017).

ITTC (2014) *Recommended Procedures and Guidelines - 1978 ITTC performance prediction method 7.5-02-03-01.4 (Revision 03)*.

Jimenez, J. (2004) 'Turbulent Flows Over Rough Walls', *Annual Review of Fluid Mechanics*, 36(1), pp. 173–196. doi: 10.1146/annurev.fluid.36.050802.122103.

Johansson, L.-E. (1984) 'The local effect of hull roughness on skin friction', *RINA Transactions*, 127, pp. 187–201.

Johnson, H. (2016) *In search of maritime energy management*. Available at: <http://publications.lib.chalmers.se/records/fulltext/233156/233156.pdf>.

Johnson, H. and Andersson, K. (2014) 'Barriers to energy efficiency in shipping', *WMU Journal of Maritime Affairs*. doi: 10.1007/s13437-014-0071-z.

Kamino, K. (2006) 'Barnacle Underwater Attachment', in Smith, A. M. and Callow, J. A. (eds) *Biological Adhesives*. Berlin: Springer-Verlag, pp. 145–166. doi: 10.1007/978-3-540-31049-5_8.

Kolter, R. and Watnick Paula (2000) 'Biofilm, City of Microbes', *Journal of bacteriology*, 182(10), pp. 2675–2679.

Kouh, J.-S., Chen, Y.-J. and Chau, S.-W. (2009) 'Numerical study on scale effect of form factor', *Ocean Engineering*, 36(5), pp. 403–413. doi: 10.1016/j.oceaneng.2009.01.011.

Lagerström, M. *et al.* (2018) 'In situ release rates of Cu and Zn from commercial antifouling paints at different salinities', *Marine Pollution Bulletin*. Elsevier, 127(December 2017), pp. 289–296. doi: 10.1016/j.marpolbul.2017.12.027.

Lagerström, M. (2019) *Occurrence and environmental risk assessment of antifouling paint biocides from leisure boats*. Stockholm University.

Lamers, B. (2018) *Ultrasonic antifouling grows as 'green' option for vessel owners*. Available at: <https://lscare.nl/ultrasonic-antifouling-grows-as-green-option-for-vessel-owners/> (Accessed: 17 July 2019).

Larsson, L. and Raven, H. C. (2010a) *Decomposition of Resistance*. In: *The Principles of Naval Architecture Series - Ship Resistance and Flow*. Jersey City (NJ): The Society of Naval Architects and Marine Engineers.

Larsson, L. and Raven, H. C. (2010b) *Experimental Resistance Prediction and Flow Measurement*. In: *The Principles of Naval Architecture Series - Ship Resistance and Flow*. Edited by J. R. Paulling. Jersey City (NJ): The Society of Naval Architects and Marine Engineers.

Larsson, L. and Raven, H. C. (2010c) *The Flow Around the Hull and the Viscous Resistance*. In: *The Principles of Naval Architecture Series - Ship Resistance and Flow*. Edited by J. R. Paulling. Jersey City (NJ): The Society of Naval Architects and Marine

Engineers.

Leer-Andersen, M. (2018) *Slutrapport för "Ytfriktionsdatabas för maritima sektorn" [RE40147243-02-00-A]*. Gothenburg.

Lejars, M., Margaillan, A. and Bressy, C. (2012) 'Fouling release coatings: A nontoxic alternative to biocidal antifouling coatings', *Chemical Reviews*, 112(8), pp. 4347–4390. doi: 10.1021/cr200350v.

Lewthwaite, J. C., Molland, A. F. and Thomas, K. W. (1984) 'An investigation into the variation of ship skin frictional resistance with fouling', *RINA Transactions*, 127, pp. 269–284.

Lindholdt, A. *et al.* (2015) 'Effects of biofouling development on drag forces of hull coatings for ocean-going ships: a review', *Journal of Coatings Technology and Research*, 12(3), pp. 415–444. doi: 10.1007/s11998-014-9651-2.

Malone, J. A. (1980) 'Effects of Hull Foulants and Cleaning/Coating Practices on Ship Performances and Economics', *Transactions - Society of Naval Architects and Marine Engineers*, 88, pp. 75–101.

McKenzie, L. a., Brooks, R. and Johnston, E. L. (2011) 'Heritable pollution tolerance in a marine invader', *Environmental Research*. Elsevier, 111(7), pp. 926–932. doi: 10.1016/j.envres.2010.12.007.

Menesses, M. *et al.* (2017) 'Measuring a critical stress for continuous prevention of marine biofouling accumulation with aeration', *Biofouling*. Taylor & Francis, 33(9), pp. 703–711. doi: 10.1080/08927014.2017.1359574.

MEPC (2019) *Marine Environment Protection Committee (MEPC), 74th session, 13-17 May 2019 - Meeting Summary*.

Monty, J. P. *et al.* (2016) 'An assessment of the ship drag penalty arising from light calcareous tubeworm fouling', *Biofouling*, 32(4), pp. 451–464. doi: 10.1080/08927014.2016.1148140.

Morrisey, D. *et al.* (2013) *In-water cleaning of vessels: Biosecurity and chemical contamination risks*. Wellington, New Zealand: Ministry of Primary Industries.

Morrisey, D. and Woods, C. M. C. (2015) *In-water cleaning technologies: Review of information Prepared for Ministry for Primary Industries*. Wellington (New Zealand). Available at: <http://www.mpi.govt.nz/news-and-resources/publications/>.

Mortensen, J. D. (2013) *Resistance of Protective Coatings to High Pressure Water Jets for Invasive Mussel Removal*. Denver, Colorado.

Moser, C. S. *et al.* (2017) 'Quantifying the extent of niche areas in the global fleet of commercial ships: the potential for "super-hot spots" of biofouling', *Biological Invasions*. Springer International Publishing, 19(6), pp. 1745–1759. doi: 10.1007/s10530-017-1386-4.

Munk, T., Kane, D. and Yebra, D. M. (2009) 'The effects of corrosion and fouling on the performance of ocean-going vessels: a naval architectural perspective', in Hellio, C. and

Yeber, D. (eds) *Advances in marine antifouling coatings and technologies*. Oxford (UK): Woodhead Publishing Limited, pp. 148–176. doi: 10.1533/9781845696313.1.148.

Murphy, E. A. K. *et al.* (2019) 'Roughness effects of diatomaceous slime fouling on turbulent boundary layer hydrodynamics', *Biofouling*. Taylor & Francis, 0(0), pp. 1–12. doi: 10.1080/08927014.2018.1517867.

Naval Sea Systems Command (2006) 'Chapter 081 – Water-borne underwater hull cleaning of Navy ships', in *Naval Ship's Technical Manual*. Washington DC.

Nendza, M. (2007) 'Hazard assessment of silicone oils (polydimethylsiloxanes, PDMS) used in antifouling/foul-release-products in the marine environment', *Marine Pollution Bulletin*, 54(8), pp. 1190–1196. doi: 10.1016/j.marpolbul.2007.04.009.

New Zealand Government (2018) *Craft Risk Management Standard - Biofouling on vessels arriving to New Zealand (15 November 2018)*, Ministry of Primary Industries. Available at: <https://www.mpi.govt.nz/dmsdocument/11668-biofouling-on-vessels-arriving-to-new-zealand-craft-risk-management-standard> (Accessed: 18 July 2019).

Niebles Atencio, B. and Chernoray, V. (2019) 'A resolved RANS CFD approach for drag characterization of antifouling paints', *Ocean Engineering*. Elsevier Ltd, 171(January 2018), pp. 519–532. doi: 10.1016/j.oceaneng.2018.11.022.

Nikuradse, J. (1933) *Strömungsgesetze in rauhen Rohren [Laws of Flow in Rough Pipes]*. Forschungsheft 361 [translated as National Advisory Committee for Aeronautics, 1950, Technical Memorandum 1292]. Göttingen (DE): Verein Deutscher Ingenieure - Verlag. doi: 10.1063/1.1715007.

Paereli, S. and Krapp, A. (2017) 'Hull and propeller performance... on an absolute scale?', in *2nd Hull Performance & Insight Conference (HullPIC'17)*. Ulrichshusen, pp. 282–292.

Pagoropoulos, A. *et al.* (2017) 'Economic and Environmental Impact Trade-Offs Related to In-Water Hull Cleanings of Merchant Vessels', *Journal of Industrial Ecology*, 0(0), pp. 1–14. doi: 10.1111/jiec.12627.

Park, J. S. and Lee, J. H. (2017) 'Sea-trial verification of ultrasonic antifouling control', *Biofouling*. Taylor & Francis, 34(1), pp. 1–13. doi: 10.1080/08927014.2017.1409347.

Perry, A. E. and Li, J. D. (1990) 'Experimental support for the attached-eddy hypothesis in zero-pressure-gradient turbulent boundary layers', *Journal of Fluid Mechanics*, 218, p. 405. doi: 10.1017/S0022112090001057.

Piazza, V. *et al.* (2018) 'A new approach to testing potential leaching toxicity of fouling release coatings (FRCs)', *Marine Environmental Research*. Elsevier, 141(March), pp. 305–312. doi: 10.1016/j.marenvres.2018.09.024.

Piola, R. F., Dafforn, K. a and Johnston, E. L. (2009) 'The influence of antifouling practices on marine invasions.', *Biofouling*, 25(7), pp. 633–644. doi: 10.1080/08927010903063065.

Plutarch (no date) 'Symposiacs', in Hamm, J. *et al.* (eds) *Essays and Miscellanies*. 5th (2013). London: Project Gutenberg. Available at: www.gutenberg.org.

- Radenovic, J. *et al.* (2014) 'New Technology for fouling defense: Fusion of biocide and Hydrogel-based Technologies', in *Corrosion 2014*. San Antonio, Texas (USA), pp. 1–15.
- Ralston, E. and Swain, G. W. (2009) 'Bioinspiration - the solution for biofouling control?', *Bioinspiration & biomimetics*, 4(1), p. 015007. doi: 10.1088/1748-3182/4/1/015007.
- Raptodimos, Y. *et al.* (2015) 'Defining Ship Structural & Machinery Onboard Measurement Campaign for Energy Efficient Operations', *SCC2015: Shipping in Changing Climates Conference 2015*.
- Rehmatulla, N. and Smith, T. (2015) 'Barriers to energy efficiency in shipping: A triangulated approach to investigate the principal agent problem', *Energy Policy*, 84, pp. 44–57. doi: 10.1016/j.enpol.2015.04.019.
- Rompay, B. Van (2013) 'Is the Much Sought-After , Better Alternative Underwater Hull Coating System Already Here ?', *Marine Coatings*, (April).
- Schottle, R. and Brown, P. (2007) 'Copper loading assessment from in-water hull cleaning following natural fouling, Shelter Island Yacht Basin, San Diego Bay, San Diego, California', *Ports 2007*, pp. 1–10. doi: 10.1061/40834(238)30.
- Schultz, M. P. *et al.* (2000) 'A turbulent channel flow apparatus for the determination of the adhesion strength of microfouling organisms', *Biofouling*, 15(4), pp. 243–251. doi: 10.1080/08927010009386315.
- Schultz, M. P. (2000) 'Turbulent Boundary Layers on Surfaces Covered With Filamentous Algae', *Journal of Fluids Engineering*, 122(2), p. 357. doi: 10.1115/1.483265.
- Schultz, M. P. *et al.* (2003) 'Three models to relate detachment of low form fouling at laboratory and ship scale.', *Biofouling*, 19 Suppl(September 2015), pp. 17–26. doi: 10.1080/0892701031000089516.
- Schultz, M. P. (2004) 'Frictional Resistance of Antifouling Coating Systems', *Journal of Fluids Engineering*, 126(6), p. 1039. doi: 10.1115/1.1845552.
- Schultz, M. P. (2007) 'Effects of coating roughness and biofouling on ship resistance and powering', *Biofouling*, 23(5–6), pp. 331–341. doi: 10.1080/08927010701461974.
- Schultz, M. P. *et al.* (2011) 'Economic impact of biofouling on a naval surface ship.', *Biofouling*, 27(1), pp. 87–98. doi: 10.1080/08927014.2010.542809.
- Schultz, M. P. *et al.* (2015) 'Impact of diatomaceous biofilms on the frictional drag of fouling-release coatings', *Biofouling*, 31(9–10), pp. 759–773. doi: 10.1080/08927014.2015.1108407.
- Schultz, M. P. and Flack, K. A. (2007) 'The rough-wall turbulent boundary layer from the hydraulically smooth to the fully rough regime', *Journal of Fluid Mechanics*, 580, pp. 381–405. doi: 10.1017/S0022112007005502.
- Schultz, M. P., Kavanagh, C. J. and Swain, G. W. (1999) 'Hydrodynamic forces on barnacles: Implications on detachment from fouling-release surfaces', *Biofouling*, 13(4), pp. 323–335. doi: 10.1080/08927019909378388.

Schultz, M. P. and Swain, G. W. (1999) 'The Effect of Biofilms on Turbulent Boundary Layers', *Journal of Fluids Engineering*, 121(1), p. 44. doi: 10.1115/1.2822009.

Schulz, S. and Pastuch, J. (2003) 'How one shipyard is making paint removal cleaner and greener', *Journal of Protective Coatings and Linings*, 20(7), pp. 50–54.

Scianni, C. and Georgiades, E. (2019) 'Vessel In-Water Cleaning or Treatment: Identification of Environmental Risks and Science Needs for Evidence-Based Decision Making', *Frontiers in Marine Science*, 6(462), pp. 1–12. doi: 10.3389/fmars.2019.00467.

Shockling, M. A., Allen, J. J. and Smits, A. J. (2006) 'Roughness effects in turbulent pipe flow', *Journal of Fluid Mechanics*, 564, pp. 267–285. doi: 10.1017/S0022112006001467.

Sofiev, M. *et al.* (2018) 'Cleaner fuels for ships provide public health benefits with climate tradeoffs', *Nature Communications*, 9(1), pp. 1–12. doi: 10.1038/s41467-017-02774-9.

Song, S., Demirel, Y. K. and Atlar, M. (2019) 'An investigation into the effect of biofouling on the ship hydrodynamic characteristics using CFD', *Ocean Engineering*. Elsevier Ltd, 175, pp. 122–137. doi: 10.1016/j.oceaneng.2019.01.056.

Speranza, N. *et al.* (2019) 'Modelling of hull roughness', *Ocean Engineering*. Elsevier Ltd, 174(April 2018), pp. 31–42. doi: 10.1016/j.oceaneng.2019.01.033.

Stacey, A. and Stacey, J. (2012) 'Integrating Sustainable Development into Research Ethics Protocols Centre for Sustainability in Mining and Industry', University of the', *Electronic Journal of Business Research Methods*, 10(2), pp. 54–63.

Stoodley, P. *et al.* (1998) 'Oscillation characteristics of biofilm streamers in turbulent flowing water as related to drag and pressure drop', *Biotechnology and Bioengineering*, 57(5), pp. 536–544. doi: 10.1002/(SICI)1097-0290(19980305)57:5<536::AID-BIT5>3.0.CO;2-H.

Stopford, M. (2009) *Maritime Economics*. 3rd edn. Oxford (UK): Routledge.

Svensen, T. E. (1983) *A techno-economic model of ship operation with special reference to hull and propeller maintenance in the face of uncertainty (Volume 1)*. University of Newcastle Upon Tyne.

Swain, G. W. and Lund, G. (2016) 'Dry-Dock Inspection Methods for Improved Fouling Control Coating Performance', *Journal of Ship Production and Design*, 32(3), pp. 1–8. doi: 10.5957/JSPD.32.3.150038.

Swain, G. W. and Schultz, M. P. (1996) 'The testing and evaluation of non-toxic antifouling coatings', *Biofouling*, 10(1–3), pp. 187–197. doi: 10.1080/08927019609386279.

Sylvester, F. *et al.* (2011) 'Hull fouling as an invasion vector: can simple models explain a complex problem?', *Journal of Applied Ecology*, 48(2), pp. 415–423. doi: 10.1111/j.1365-2664.2011.01957.x.

Tait, M. and Larson, B. M. H. (2018) 'Entropy and the conceit of biodiversity management', *Global Ecology and Biogeography*, 27(6), pp. 642–646. doi: 10.1111/geb.12733.

- Takata, L., Falkner, M. and Gilmore, S. (2006) *Commercial Vessel Fouling in California: analysis, evaluation, and recommendations to reduce nonindigenous species release from the non-ballast water vector*.
- Tillig, F. *et al.* (2018) 'Analysis of uncertainties in the prediction of ships' fuel consumption—from early design to operation conditions', *Ships and Offshore Structures*, 13, pp. 13–24. doi: 10.1080/17445302.2018.1425519.
- Townsin, R. L. *et al.* (1980) 'Speed, power and roughness: the economics of outer bottom maintenance', *Naval Architect*, (2), pp. 459–483.
- Townsin, R. L. (2003) 'The ship hull fouling penalty', *Biofouling*, 19, pp. 9–15. doi: 10.1080/0892701031000088535.
- Townsin, R. L. (2013) 'A note on current anti-fouling issues', in *International Conference on Marine Coatings*. London.
- Townsin, R. L. and Anderson, C. D. (2009) 'Fouling control coatings using low surface energy, foul release technology', *Advances in Marine Antifouling Coatings and Technologies*, pp. 693–708. doi: 10.1533/9781845696313.4.693.
- Tribou, M. and Swain, G. (2017) 'The effects of grooming on a copper ablative coating: a six year study', *Biofouling*. Taylor & Francis, 33(6), pp. 494–504. doi: 10.1080/08927014.2017.1328596.
- Tribou, M. and Swain, G. W. (2015) 'Grooming using rotating brushes as a proactive method to control ship hull fouling', *Biofouling*, 31(4), pp. 309–319. doi: 10.1080/08927014.2015.1041021.
- UN (2019) *World Population Prospects 2019, DESA Population Division*. Available at: <https://population.un.org/wpp/> (Accessed: 11 July 2019).
- Ünal, U. O. (2015) 'Correlation of frictional drag and roughness length scale for transitionally and fully rough turbulent boundary layers', *Ocean Engineering*, 107, pp. 283–298. doi: 10.1016/j.oceaneng.2015.07.048.
- UNCTAD (2018) *Review of Maritime Transport 2018*. New York (NY). doi: 10.15388/slavviln.2018.63.11867.
- Watermann, B. *et al.* (1997) 'Performance and effectiveness of non-stick coatings in seawater', *Biofouling*, 11(2), pp. 101–118. doi: 10.1080/08927019709378323.
- Watermann, B. T. *et al.* (2005) 'Bioassays and selected chemical analysis of biocide-free antifouling coatings', *Chemosphere*, 60(11), pp. 1530–1541. doi: 10.1016/j.chemosphere.2005.02.066.
- Webster, D. C., Pieper, R. J. and Nasrullah, M. J. (2010) 'Zwitterionic/amphiphilic pentablock copolymers and coatings therefrom'. International.
- Weinell, C. E. and Yebra, D. M. (2009) 'Key issues in the formulation of marine antifouling paints', *Advances in Marine Antifouling Coatings and Technologies*, (Chapter 17), pp. 308–333. doi: 10.1533/9781845696313.2.308.

Woods, C. M. C., Floerl, O. and Jones, L. (2012) 'Biosecurity risks associated with in-water and shore-based marine vessel hull cleaning operations', *Marine Pollution Bulletin*. Elsevier Ltd, 64(7), pp. 1392–1401. doi: 10.1016/j.marpolbul.2012.04.019.

Woods Hole Oceanographic Institute (1952) *Marine fouling and its prevention*. Menasha, WI: George Banta Publishing Co.

Yebra, D. M. and Català, P. (2011) 'Smooth operator', *The Naval Architect*, January, pp. 16–28.

Yebra, D. M., Kiil, S. and Dam-Johansen, K. (2004) 'Antifouling technology - Past, present and future steps towards efficient and environmentally friendly antifouling coatings', *Progress in Organic Coatings*, 50(2), pp. 75–104. doi: 10.1016/j.porgcoat.2003.06.001.

Yeginbayeva, I. A. and Atlar, M. (2018) 'An experimental investigation into the surface and hydrodynamic characteristics of marine coatings with mimicked hull roughness ranges', *Biofouling*. Taylor & Francis, 0(0), pp. 1–19. doi: 10.1080/08927014.2018.1529760.

Ytreberg, E. *et al.* (2019) 'Effects of scrubber washwater discharge on microplankton in the Baltic Sea', *Marine Pollution Bulletin*. Elsevier, 145(May), pp. 316–324. doi: 10.1016/j.marpolbul.2019.05.023.

Ytreberg, E., Karlsson, J. and Eklund, B. (2010) 'Comparison of toxicity and release rates of Cu and Zn from anti-fouling paints leached in natural and artificial brackish seawater', *Science of the Total Environment*. Elsevier B.V., 408(12), pp. 2459–2466. doi: 10.1016/j.scitotenv.2010.02.036.

Zabin, C. *et al.* (2018) 'How will vessels be inspected to meet emerging biofouling regulations for the prevention of marine invasions?', *Management of Biological Invasions*, 9(3), pp. 195–208. doi: 10.3391/mbi.2018.9.3.03.

Zargiel, K. A. and Swain, G. W. (2014) 'Static vs dynamic settlement and adhesion of diatoms to ship hull coatings.', *Biofouling*, 30(1), pp. 115–29. doi: 10.1080/08927014.2013.847927.