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New Developments in Hull Fouling Management Options

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Abstract

This paper surveys recent developments for biocide-free antifouling solutions. On the coating side, nano-coatings including graphene-based coatings, coatings with passive air lubrication, and biocide-free SPC (self-polishing copolymers) are covered. Active protection systems based on ultrasonic or ultraviolet radiation have progressed significantly in recent years. Robotic cleaning shows rapid growth in technological and business maturity, enabling hard coatings as a viable option to replace the current standard solution of biocide-containing SPC coatings.

1. Antifouling as an ecological and economic necessity

1.1. A problem as old as shipping

Fouling has been a headache for shipping since ancient times, *Bertram and Yebra (2017), Doran (2019), Bertram (2020)*. Over the centuries, human ingenuity has come up with various countermeasures to prevent or reduce fouling, lumped here collectively under the term "antifouling".

The most widely adopted antifouling solution in modern shipping has been antifouling SPC (self-polishing copolymers) paints, where the coating matrix containing the biocides dissolved slowly in water, Fig.1. The release of biocides and paint particles (microplastics) is significantly accelerated under abrasive forces as experienced in hull cleaning with brushes. IMO has banned two biocides for antifouling coatings on ship hulls so far, namely TBT (tributyltin) since 2003 and Cybutryne since 2023. Further substances are under scrutiny, resulting in regional bans and proposals to add them to the list of antifouling substances banned by IMO.

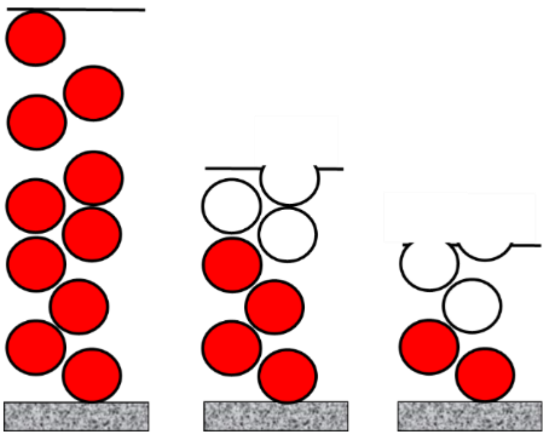

Fig.1: Principle of SPC with biocides (red) and leached layer (empty circles)

Biocidal antifouling coatings have fueled also a debate on in-water cleaning of ships. Over the past decade, more and more port authorities have banned in-water cleaning in their ports. This is partly due to the fear that aquatic invasive species may be released and spread uncontrollably threatening the local ecosystem, but another concern is that the cleaning will release biocides and microplastics which will settle and contaminate the soil.

As such, biocidal antifouling paints are now widely seen as a bridging technology. But what could be on the other side of the bridge? World shipping moves slowly, but steadily towards sustainable shipping. Leaching copper and micro-plastics (the dissolved ingredients of today's standard SPC coatings) into the world oceans is not sustainable. *Dafforn et al. (2011)* argue "that the way forward is to phase-out metals and organic biocides from [antifouling] paints and to adopt non-toxic alternatives.

[…] However, we call for caution in the time-frame for making these changes." There is no shortage of ideas, but the road from concept to deployment is often a long one. This is especially true for antifouling, where a product's success and effectiveness are generally measured over at least five years, the standard interval for ships to be drydocked for cleaning and new coating.

We cannot simply abolish biocidal SPCs, as antifouling measures for ships are both an ecological and economic necessity.

1.2. Key role of antifouling for energy efficiency in ship operation

Marine growth can decrease ship performance drastically, resulting in a 30-50% increase of fuel consumption (and associated emissions) compared to a smooth hull, Fig.2. The effect of even light slime is with up to 20% fuel increase larger than widely thought, *GIA (2023)*. *CSC (2011)* estimates the financial impact of fouling to 30 billion USD per year for the world fleet, and the contribution to man-made CO_2 emissions to 0.3%.

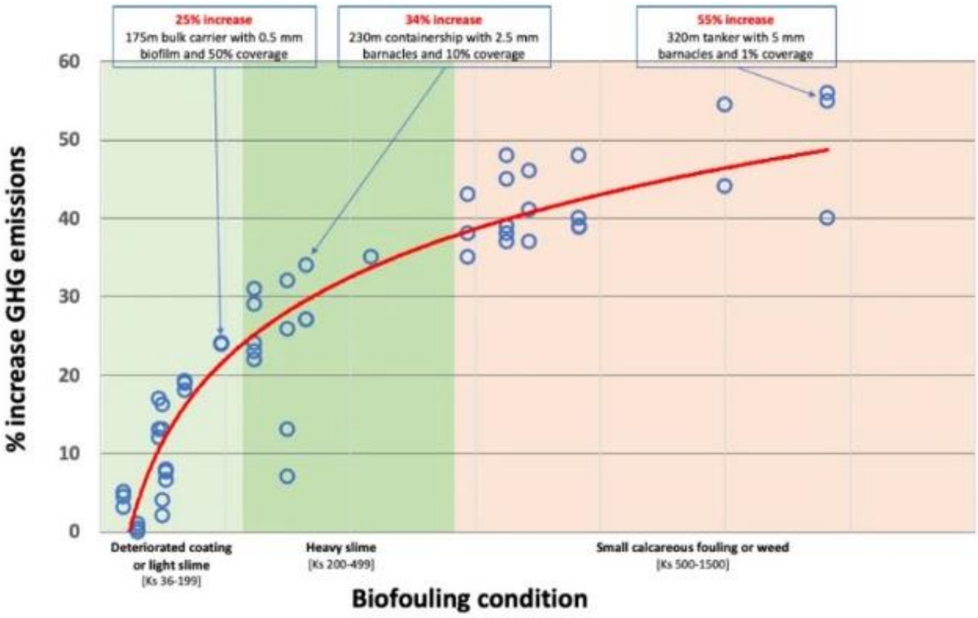

Fig.2: Effect of biofouling on fuel consumption and CO_2 emissions, *GIA (2023)*

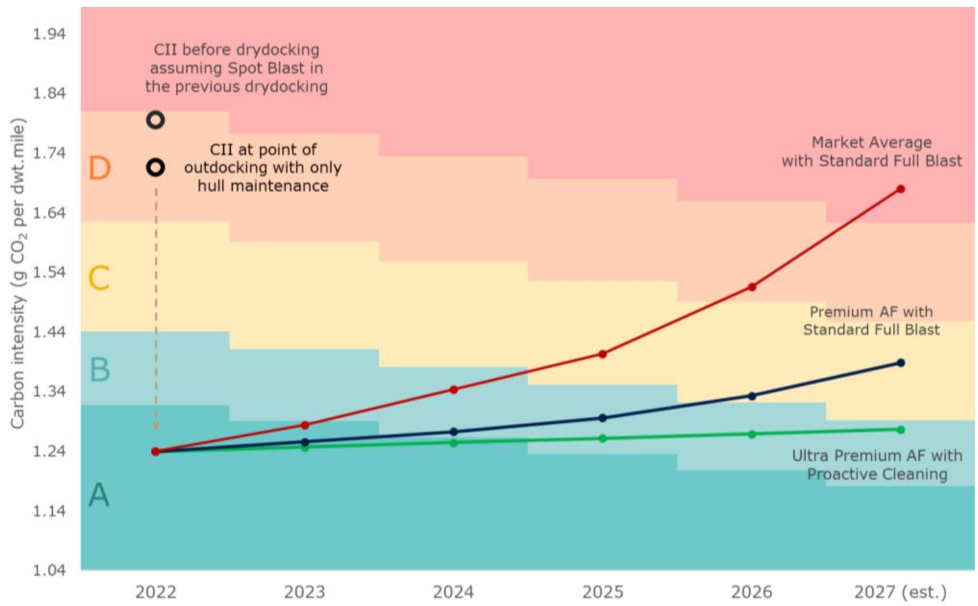

Fig.3: Projected CII development of different coating and cleaning options, source: Jotun

Progressing fouling can deteriorate a ship's CII (Carbon Intensity Indicator) rating from an A to an E within 5 years, Fig.3, *Tan et al. (2022)*. On the other hand, optimum coating and cleaning strategies can maintain hull performance largely, with a deterioration from A to B within five years, mainly due to the increasingly stricter thresholds on the CII rating, Fig.3. Despite the significantly higher CAPEX, the resultant lower OPEX for fuel make ultra premium coatings often a convincing business case.

1.3. Biofouling management to prevent transport of aquatic invasive species

After IMO's ballast water management convention went into force in 2017, hull fouling has become the main contributor for the spread of aquatic invasive species. For energy efficiency, the key focus lies on the large surfaces, such as ships sides. For prevention of invasive species, the key focus lies on niche areas which are hard to clean. Besides IMO's 2011 Guidelines for the Control and Management of Ships' Biofouling to Minimize the Transfer of Invasive Aquatic Species, revised in 2023, various organisations have recently proposed guidelines for the cleaning of hulls, such as Jotun, *Oftedahl and Enström (2020)*, and BIMCO, *Sørensen (2020)*, *BIMCO (2021)*.

2. New developments in coating technology

2.1. Nano-coatings

'Nano-coatings' use bio-inspired microscopic surface structures (e.g. shark skin, lotus effect) to make adhesion difficult for organisms, Fig.4. Nano-coatings are expected to have better long-term performance than low-surface energy foul-release coatings ('silicone paints') which degrade as the silicone film weathers, *Bertram and Yebra (2017)*. Several nano-coating products are already on the market, Fig.4. Stolt Tankers announced in 2023 that 25 of their tankers will have their propellers coated with graphene-based nano-coating, Fig.5.

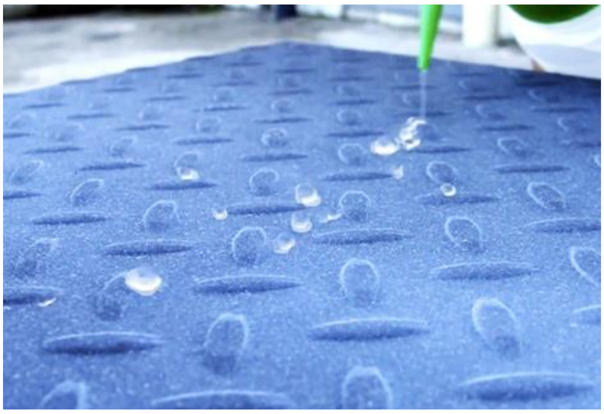

Fig.4: Nano-coating structure (left) and demonstrating non-stick effect (right), source: Ultra Ever Dry

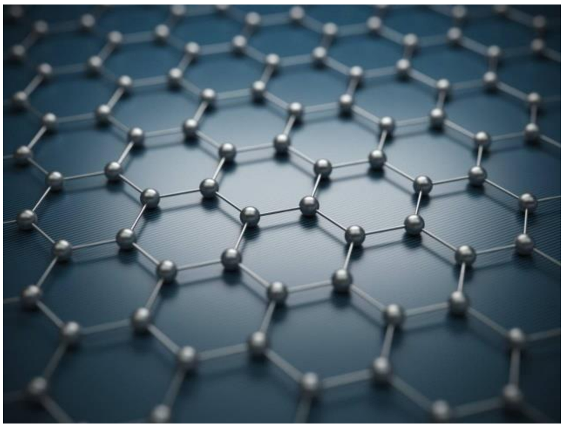

Fig.5: Graphene (left) is the base for the nano-coating on propellers of Stolt Tankers (right)

2.2. Biocide-free SPCs

Nippon Paint Marine has developed an innovative biocide-free SPC antifouling paint for ships. Here the slowly dissolving coating with a special micro-structure apparently prevents adhesion of fouling as the marine organisms do not recognize the coating as a surface: “when marine life finds the micro-domain surface, they are confused and hesitate to try to adhere there because they do not recognise the microdomain surface as a place where they can easily develop,” *Yamashita (2022).*

2.3. Passive air lubrication

The AIRCOAT (AIR-induced friction reducing ship COATing) project, https://aircoat.eu/, has developed foils with a surface structure mimicking floating ferns (Salvinia), which trap a fine film of air, Fig.6, *Oeffner et al. (2020), Walheim et al. (2022)*. In 2021, field tests showed that the foils work at least in the short terms, but more time is needed to assess the long-term performance in practical applications.

While the focus here is on reducing resistance through passive air lubrication, note that *Silberschmidt et al. (2016)* report that active air lubrication may substitute antifouling coatings, as apparently the change between water and air saturated water inhibits marine growth on the ship bottom.

Fig.6: Floating fern (left) inspired the passive air-trapping foil (right) in the AIRCOAT project

3. Ultra-X protection methods

3.1. Ultrasonic technology

Ultrasonic vibrations cause very high accelerations, which destroy cell structures of fouling. A strong point of ultrasonic protection is that it offers biocide-free protection for ships even at zero speed. The technology has progressed from research to industrial applications. More recently, ‘intelligent’ dynamic biofilm protection has been developed, where Artificial Intelligence sets the optimum parameters for each transducer based on assorted sensor information, Fig.7, *Mayorga et al. (2023)*.

Fig.7: DBPI from Hasytec

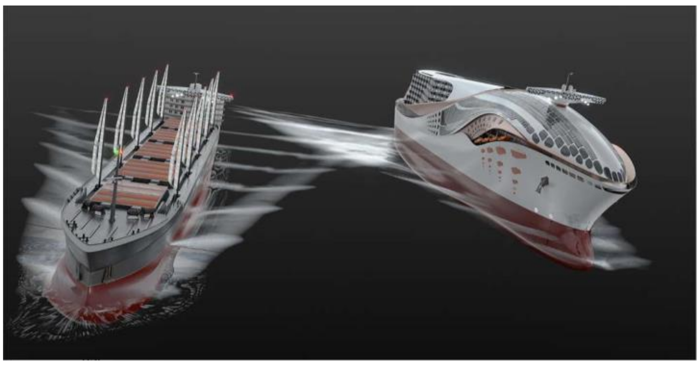

Fig.8: CHEK cases for full hull ultrasonic protection

The technology is by now widely adopted for niche areas on ships, such as sea chests, bow thrusters, heat exchangers, and propellers. Current protective range of ultrasonic transducers is ~6-8m. For a cargo-ship, this would mean hundreds of transducers to protect the full in-water hull. The CHEK project, https://www.projectchek.eu/, *Kelling (2021)*, investigates the feasibility of doing just this, with a bulk carrier and a cruise ship as application cases, Fig.8.

3.2. Ultraviolet technology

Ultraviolet (UV) radiation is widely used in ballast water treatment. It has been proposed for hull antifouling decades ago, Benson et al. (1973). The rapid attenuation of UV radiation and relatively high initial and operational costs has made this option rather unattractive for external antifouling applications. This may change now. AkzoNobel, Philips, and since 2023 also Damen Shipyards, have developed a novel fouling prevention solution, based on the generation of UV light by LEDs embedded in a transparent layer, Fig.9 (left), *Salters et al. (2022)*. The LEDs form thin tiles, relatively light-weight and thin. The tiles are 100% watertight and powered via wireless power transfer, thus substantially reducing any chance of electrical shorts. The technology is in the prototype stage, Fig.9 (right).

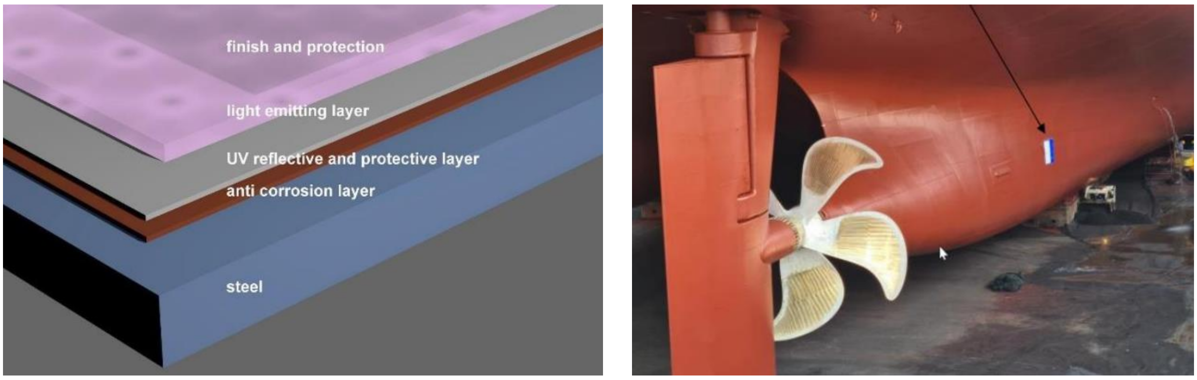

Fig.9: Principle of UVC LED foil application (left) and tile installation on LNG carrier (right)

4. Robotic cleaning and inspection

4.1. Proactive cleaning (grooming)

Fig.10: Effect of proactive cleaning, *GIA (2022)*

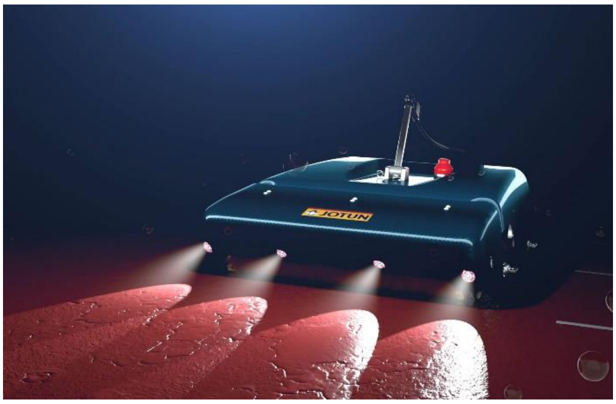

Fig.11: Hull Skater robot, source: Jotun

Proactive cleaning (a.k.a. grooming) has been increasingly advocated as a key measure to reduce fuel consumption and the CII in service. Such frequent, soft cleaning at biofilm stage keeps hull performance degradation in check, resulting in significant in-between docking fuel savings, Fig.10.

For effective proactive cleaning, cleaning technology and coating technology should be matched. Jotun's Hull Skating Solution is a prime example for this, *Oftedahl and Enström (2020)*, combining a high-performance, abrasion-resistant coating allowing frequent cleaning without coating erosion;

performance monitoring based on ISO 19030 for decision support on when to clean; hull inspection and cleaning of biofilm by the Hull Skater robot, Fig.11, and performance-based contracts and service guarantees.

4.2. Smarter robots learn new tricks

Robotic hull cleaning has enjoyed exponential growth, moving from first research in the 1980s to mature industry services offered by various service providers, *Bertram (2021)*. The state of the art of in-water robotic cleaning and inspection continues to evolve in various aspects:

- Automatic identification and quantification of fouling using machine vision, e.g. *Guéré and Gambini (2021)*. Continuing development aims at aligning various machine vision system to use a common scale for rating of fouling on images.
- Laser scanning hull surfaces with resolution of 0.01 mm (= 10 microns) on crawling robots and 0.5 mm on free-floating robots, Fig.11, *Paranhos (2020)*. This resolution would allow quantification of macrofouling.
- Team-capable autonomous robots as the HSR robots of Armach Technology, Fig.12, *Lander (2022)*. Team capable robots can clean ship hulls in shorter time, parallelizing the work. A large cargo ship can then be cleaned during one regular port stay.

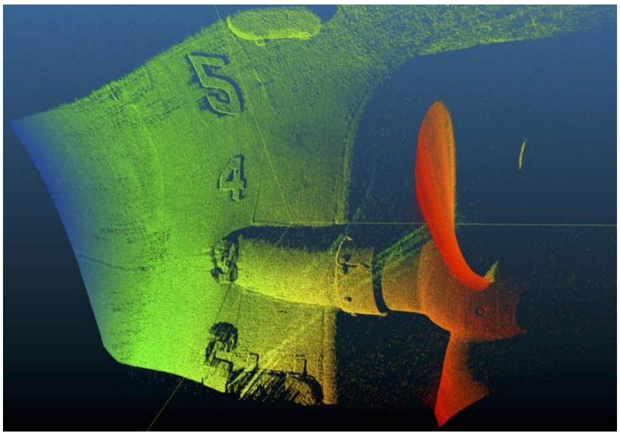

Fig.12: In-water scan from floating robot, source: Kraken Robotics

Fig.11: Team-capable HRS robots, source: Armach Robotics

4.3. In-transit cleaning

In-transit cleaning would resolve some current issues with in-water cleaning in ports, such as requirements for collection and disposal of removed fouling and paint particles and availability of cleaning services. In Norway, Shipshave pioneered in-transit cleaning of hulls with its ITCH system, *Freyer and Eide (2021)*, a semi-autonomous system for cleaning ship sides with a tethered robot that swipes up and down, using ship hydrodynamic forces for up-and-down motion and adhesion to hull. Ships ends, bottom, and niche areas cannot be cleaned by the ITCH.

Israeli startup NakAI Robotics has developed an autonomous in-transit robotic system to remove biofilm while the ship is in transit, *Nice and Aharony (2023)*. The robot self-deploys from the side of the ship, Fig.13 (left). It then autonomously moves over the hull, Fig.13 (right), using hydrodynamic forces for adhesion and UV light and soft brushes for cleaning, deemed soft enough to avoid abrasion of SPC coatings. The robot does not operate near the propeller, near the bow, or in niche areas. First prototype testing on a cargo ship was performed in 2021. Further developments shall fit the robot with class-approved inspection sensors. The robot may then be used for steel structure survey, cleaning, and fouling condition documentation.

Fig.13: NakAI robot for in-transit cleaning, https://www.nakairobotics.com/

Gerland et al. (2023) describe a German development for autonomous in-transit hull cleaning: Larabicus, a robotic 'cleaning fish', Fig.14, continuously cleans the ship's hull, removing the biofilm and thus inhibiting higher fouling stages. The Larabicus robot is agile enough to bypass attachments such as bilge keels, galvanic anodes, or openings for ballast water tanks. The concept has been tested so far only under laboratory conditions. A first pilot project on a ship in operation are envisioned for Q4 2024.

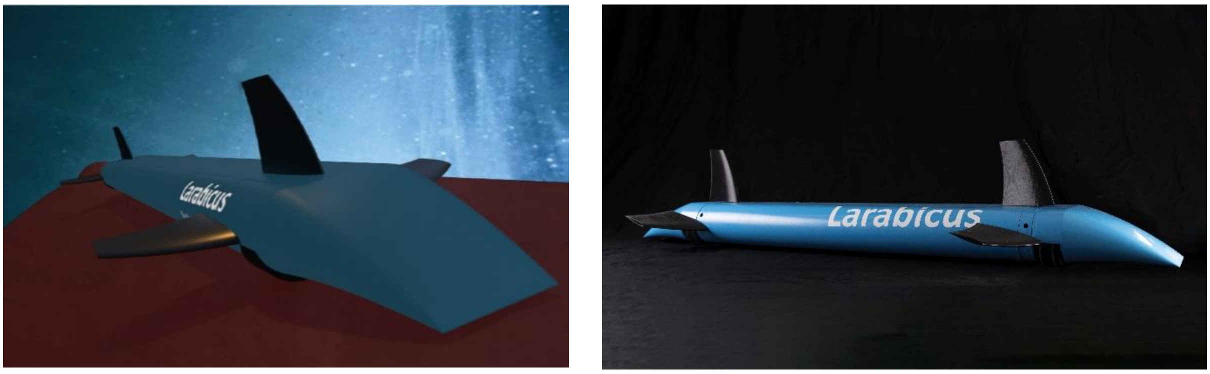

Fig.14: Larabicus robot for in-transit cleaning

5. Conclusion

Where there is a problem, there is a solution. New challenges for the shipping industry, such as increasingly strict CII requirements for operational energy efficiency and wider application of biofouling management requirements, are answered by innovative solutions. Ingenuity and entrepreneurship thrive, and established big players are kept on their toes by start-ups challenging the status quo.

The progress towards more efficient and more sustainable hull management solutions in the last five years is impressive and encouraging.

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Ultrasonic Antifouling –
An Approach to Mitigate Biofouling on Ship Hulls and Niche Areas

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Abstract

This paper presents final results of the EU R&D project CHEK for the work packages related to ultrasonic hull protection against hull and propeller fouling. The work packages and the Dynamic Biofilm Protection intelligent (DBPi) solution are described. One work package concerns the concept and installation manual for hull surface and niche areas based on construction plans for a cruise vessel and a bulk carrier. Following simulations and laboratory tests, the DBPi hardware and software were adapted. After successful factory acceptance tests, results will be examined in real life test during a 7-month demo voyage period.

1. HASYTEC story – Role in CHEK project

HASYTEC electronics was founded in 2016 as a start-up for specialising in ultrasonic cleaning technologies. These are used in professional marine as well as in land-based industry. The use of HASYTEC ultrasound prevents the formation of biofilm as well as organic and inorganic deposits. These form the basis for the decomposition of equipment, pipes and materials through biocorrosion. HASYTEC started "showing flag" and raising perception of ultrasonic hull and propeller protection against biofouling very early on, e.g. *Kelling (2017a,b).* By 2024, the company had installed more than 10000 ultrasonic tranducers in over 850 ships worldwide.

The EU R&D project CHEK (deCarbonising sHipping by Enabling Key technology symbiosis on real vessel concept designs), https://www.projectchek.eu/, has as a goal to reduce CO_2 emissions in global shipping. The focus is on the combined application of advanced key technologies in shipbuilding. The project is described in more detail in Appendix I and *Kelling (2021).* Within the CHEK project, one focus was on drag reduction technologies to reduce fuel consumption and emissions to air. HASYTEC was in charge of the work package WP6, contributing all activities and devlopment concerning ultrasonic hull and propeller biofouling protection.

2. Ultrasonic Antifouling

2.1. Short introduction to biofouling

Biofouling is the unwanted attachment of various marine plants and animals in the marine environment. Every submerged structure is susceptible to fouling and will eventually become overgrown. On ships, its significance is manifold, and different estimates have been made of the losses incurred due to biofouling, including reduction of ships speed due to frictional resistance, leading to increased fuel consumption, docking charges for ship servicing and loss of income due to downtimes, Fig.1. Another significant aspect of biofouling is the transport of invasive species. To battle these issues, often antifouling paints, containing toxic compounds are used. However, their damaging effect to the environment is leading them to be phased out of production and use. Therefore, the need for a toxic-free solution is high.

2.2. Ultrasonic antifouling technology

The basic concept in ultrasonic antifouling is to use acoustic waves in the ultrasound range to prevent the biofouling already in the biofilm stage. Although the concept has been around since around the 1960s, the optimal parameters were not known for a long time, preventing industrial adoption.

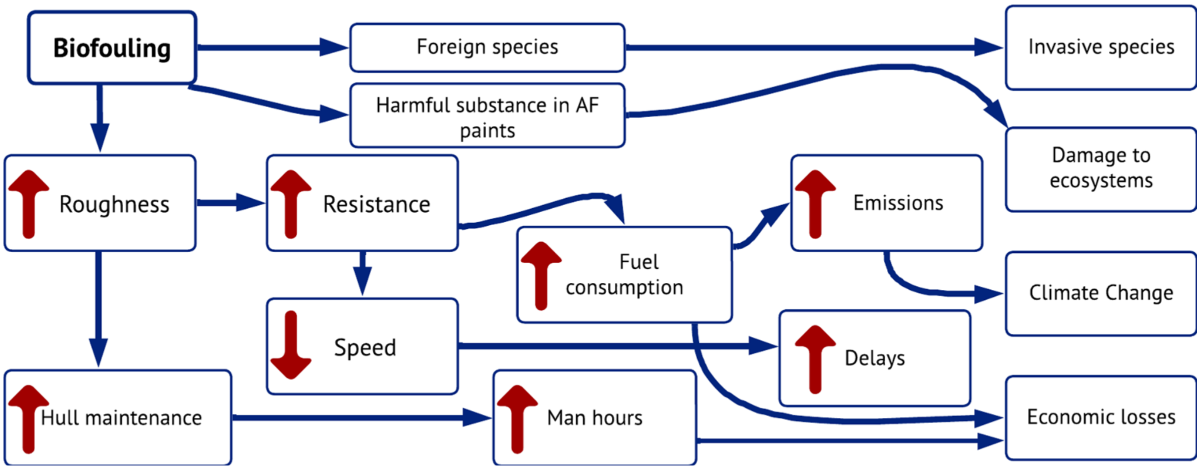

Fig.1: Effect of biofouling on shipping

To understand the wave propagation in detail, a Finite Element Analysis (FEA) approach was used now within the project, Fig.2. As coatings may lead to strong sound absorption, selecting the right paint impacts the effectiveness of the ultrasonic approach significantly and we performed lab testing to determine the most suitable coatings for ultrasonic wave transmission (Sound pressure tests and Caliometry tests for output power comparison). Once we had the concept ready, we proceeded to the prototyping.

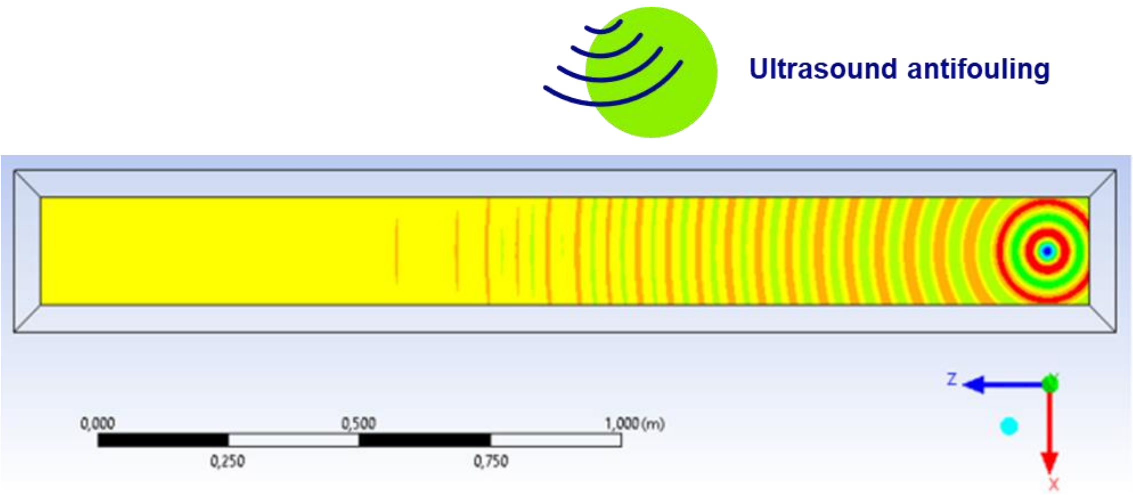

Fig.2: Laboratory testing of ultrasonic technology on coated steel plate

2.3. Installation of prototype

The development process involved several adaptations from older designs including several new features. In the hardware aspect, the control unit was adapted to host up to 16 transducers. This allows to scale up to the larger surface areas. In addition to higher power, cable lengths of up 100 m facilitated centralized installation of the system.

We used the results obtained from the simulations to develop customized transducers for ship hull applications. These were specifically designed for large-area coverage of the test patches and had an integrated measurement board that provided us with status information and environmental conditions, e.g. ambient temperatures.

The software adaptations included:

- Establishing communication with transducers

- Optimization of the software scan, aligned with the new transducers. Adjusting the frequencies, as these were in a different range.
- Design of several power programs with variable output power and pulse intervals to investigate their influence on the biofilm

Once the design was ready for production, the manufacturing of 4 hull prototype units and 12 hull transducers for testing on case vessels and 8 niche prototypes with 52 transducers was planned. That phase was challenging due to supply shortages during the Covid-19 pandemic. Nonetheless, eventually all parts were obtained and all prototypes, transducers including sensor boards and connection cables were assembled at the production facility in Kiel. Factory tests on hardware and software ensured that the prototypes worked according to specifications. For later installation on the two demo vessels, Fig.3, Table I, all parts were shipped to their destinations in Malta and China. Table II gives details of the installations. Fig.4 shows one of the installations with control unit and a typical transducer glued to the hull steel structure.

Table I: Demo vessels for installation

	MSC Seaside	Sirius Sky
Vessel type	Cruise ship	Bulk carrier
Length	323.00 m	200 m
Breadth	41.00 m	32.24 m
Tonnage	153516 tdw	34164 tdw
Built in	2017	2017


Fig.3: Demo vessels: MSC Seaside (left) and Sirius Sky (right)

Table II: Installation details

	Cruise ship	Bulk carrier
When?	November 2022	January 2022
How long?	6 days	10 days
Where?	Fincantieri shipyard, Malta	Zhoushan Jinhai yard, China
What?	Hull test patches, Seawater Supply with Sea Chests and Seawater Filters, Engine Cooling, Propeller	Hull test patches, Freshwater Generator, Propeller, Engine Cooling
Transducers installed	Niche areas: 24 Hull test patches: 6	Niche areas: 28 Hull test patches: 6

To assess the performance of the ultrasonic antifouling system, the following parameters were evaluated, Fig.5:

- Consistency and continuous operation of the software and hardware functionality
- Underwater visual inspection of the hull test patches
- Visual inspection of the seawater filters and sea chests
- Visual inspection of the propeller
- Comparison of heat exchange parameters between units with and without ultrasound antifouling

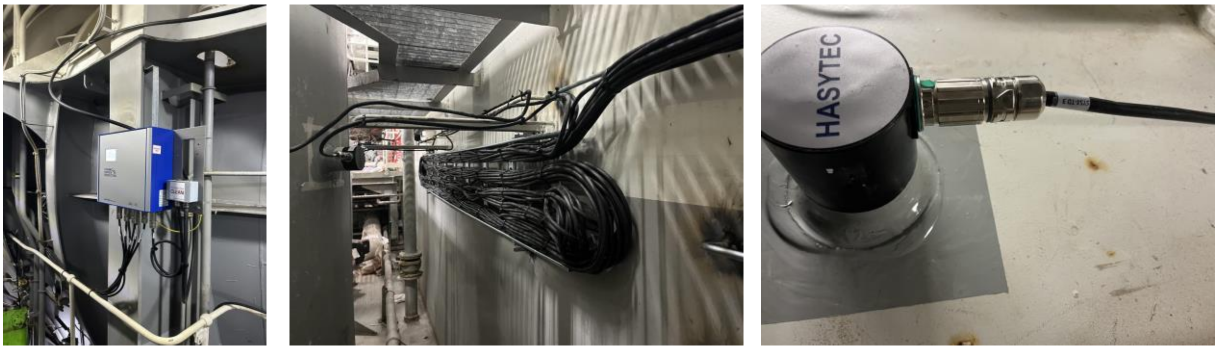

Fig.4: Installation: Control unit (left) and one transducer (center and right)

Fig.5: Monitoring of system

2.4. Results

Figs.6-8 show results from test voyage trials for niche areas.

Fig.6: Results from test voyage trials – Sea strainer after 1 year; with (left) and without (right) ultrasonic protections

The freshwater generator was also inspected, and favourable results were observed, Fig.7. No visible fouling was present. In addition, the bottom evaporator tube was also opened. This was free from any organic and inorganic deposits.

During the first underwater inspections, the sea chests were also inspected from the outside, Fig.8. Limited, but spatially inconsistent cover by barnacles were recorded on the portside.

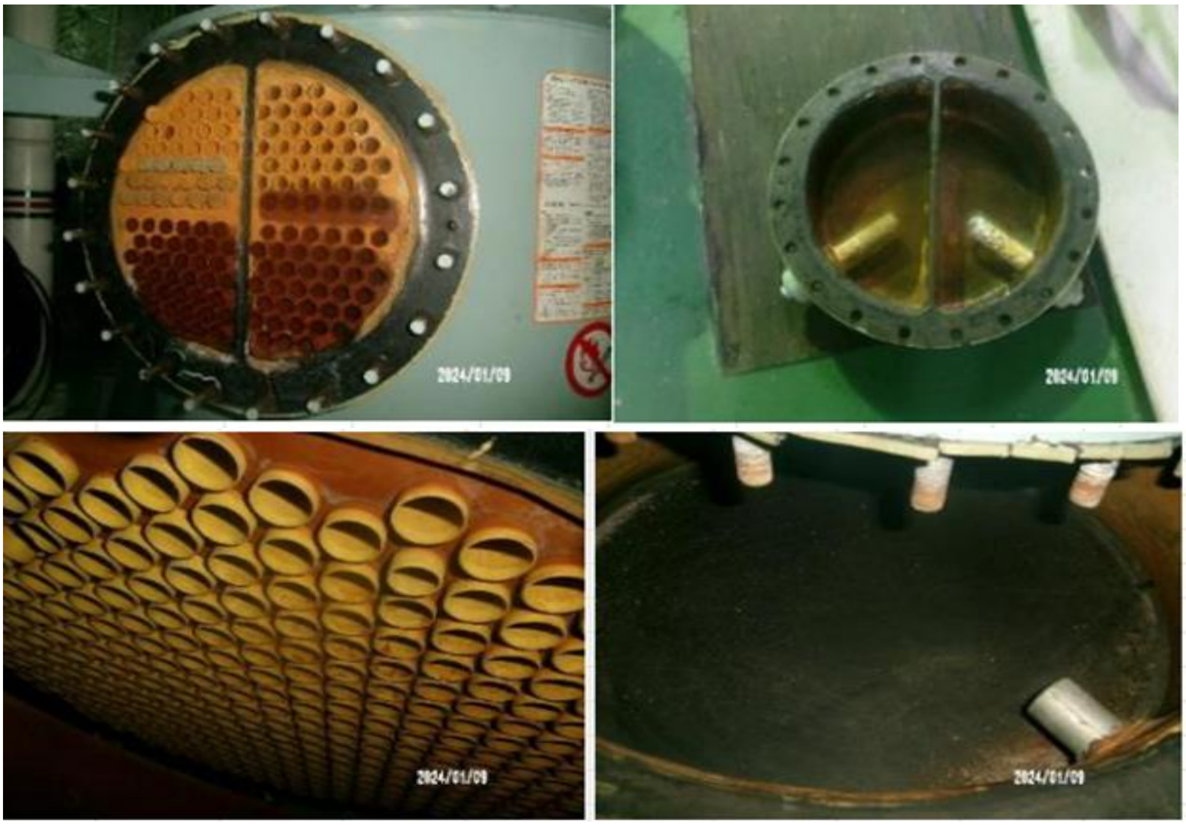

Fig.7: Results from test voyage trials – Freshwater generator

Fig.8: Results from test voyage trials – Sea chests

The results from the test hull patch inspection were favourable and only light slime was recorded after ten months of voyage, Fig.9:

- Hull Patch Examination Outcomes:
    - Performance Validation: Visual examination confirms the underwater (UW) system performs as anticipated.

- Fouling Comparison: Clear distinction noted between areas with and without transducers; areas with the UW system show significantly less fouling.

- Fouling Categories and Hull Roughness:
  - Details Provided: Descriptions of slime categories and average hull roughness for digital twin investigations are detailed in the cruise ship section.

- Fouling Condition Designation:
  - Without UW System: After a year in service, the bulk carrier's condition is designated as heavy slime.
  - With UW System: The bulk carrier equipped with the UW system is designated as light slime.

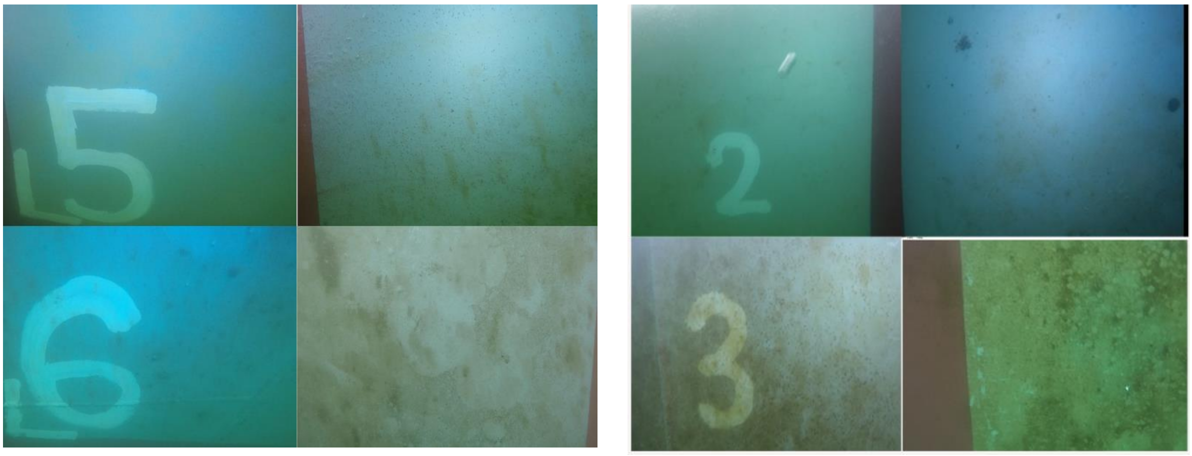

Fig.9: Hull text patches, with (top) and without (bottom) ultrasonic protection

3. Challenges and outlook

Lessons from the text voyages were:

- Inconclusive Results:
  - Favorable outcomes for the bulk carrier, less so for the cruise ship, suggesting hull transducer design may require refinement

- Transducer Development Needs:
  - Focus on reducing ultrasonic transmission losses due to impedance between hull and water
  - Explore different materials for transducer housing

- Software Implementation Challenges:
  - Difficulties in quick software changes noted
  - Future projects will develop remote access and control to quickly resolve software issues and analyze log data.

- Physical Verification and Accessibility:
  - Regular physical verification needed
  - Logistical challenges in vessel accessibility for underwater inspections due to location constraints (regulations or poor visibility)

- Vessel Selection for Future Projects:
  - Select vessels to facilitate easier and more regular data collection

- <u>Data Collection and Impact Quantification:</u>
  - Improved data Collection methods to better quantify reductions in waste streams, particularly biocides.
  - Better assessment of ultrasound system's impact on energy savings and maintenance costs

Acknowledgements

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Appendix I: CHEK project

The CHEK project was supported by the European Union with a total of 10 million Euro from the Horizon 2020 funding program, https://ec.europa.eu/programmes/horizon2020/en/home. The Horizon 2020 program is the biggest EU research & innovation program ever, with nearly € 80 billion of funding over 7 years. Its aim is combining European research and innovation to achieve excellent science, industrial leadership and tackling societal challenges. The CHEK project partners are:

- University of Vaasa (UV), http://www.uwasa.fi/, is a business-oriented, multidisciplinary, and international university.
- Wärtsilä, www.wartsila.com, is a provider of ship machinery, propulsion and manoeuvring solutions, supplying engines and generating sets, reduction gears, propulsion equipment, control systems, and sealing solutions for all types of vessels and offshore applications.
- Cargill Ocean Transportation, https://www.cargill.com/transportation/cargill-ocean-transportation, is a freight-trading business that provides bulk shipping services to customers across the globe.
- MSC Cruises, www.msccruises.com, is a global cruise line, which is part of the Cruises Division of MSC Group, the privately held Swiss-based shipping and logistics conglomerate.
- Lloyd's Register EMEA (LR), www.lr.org, is part of the Lloyd’s Register Group, a global independent risk management and safety assurance organisation that works to enhance safety and improve the performance of assets and systems at sea, on land and in the air.
- World Maritime University (WMU), www.wmu.se, was established in 1983 by the International Maritime Organization (IMO).
- Silverstream Technologies, https://www.silverstream-tech.com/, was established in 2010 and the company specialises in Air Lubrication Technology, Silberschmidt et al. (2016), which is designed to reduce the frictional impact between the flat bottom of the ship hull and water.
- HASYTEC Electronics GmbH, https://www.hasytec.de/, is market leader in ultrasound based antifouling technology.
- Deltamarin, https://deltamarin.com/, is a ship engineering and design company.
- Climeon AB, https://climeon.com/, has well proven technology to convert waste heat to clean power.
- BAR Technologies, https://www.bartechnologies.uk/, have used its in-house tool ShipSEAT to design and optimise their own patented and trademarked wind propulsion system called WindWings, https://www.bartechnologies.uk/project/windwings/.

The project aims to combine a variety of innovative technologies to achieve its goals of significant increase (>50%) of energy efficiency and virtual elimination (>99%) of greenhouse gases, Fig. I.1:

- New energy technologies
  - Fixed wing sails
  - Fuel-cell ready hydrogen engine
- Operational technologies and practices
  - Automated vessel routing/sailing
  - Cruise vessel itinerary optimization
- Propulsion/Power supply technologies
  - Fuel-flexible gas engine incl. over-the-air software updates
  - Scalable power plant
  - Hybrid energy management
  - Waste heat recovery
  - Waste-to-power
- Drag reduction technologies
  - Gate rudder
  - Air lubrication
  - Ultrasound antifouling
  - Ship hull optimization

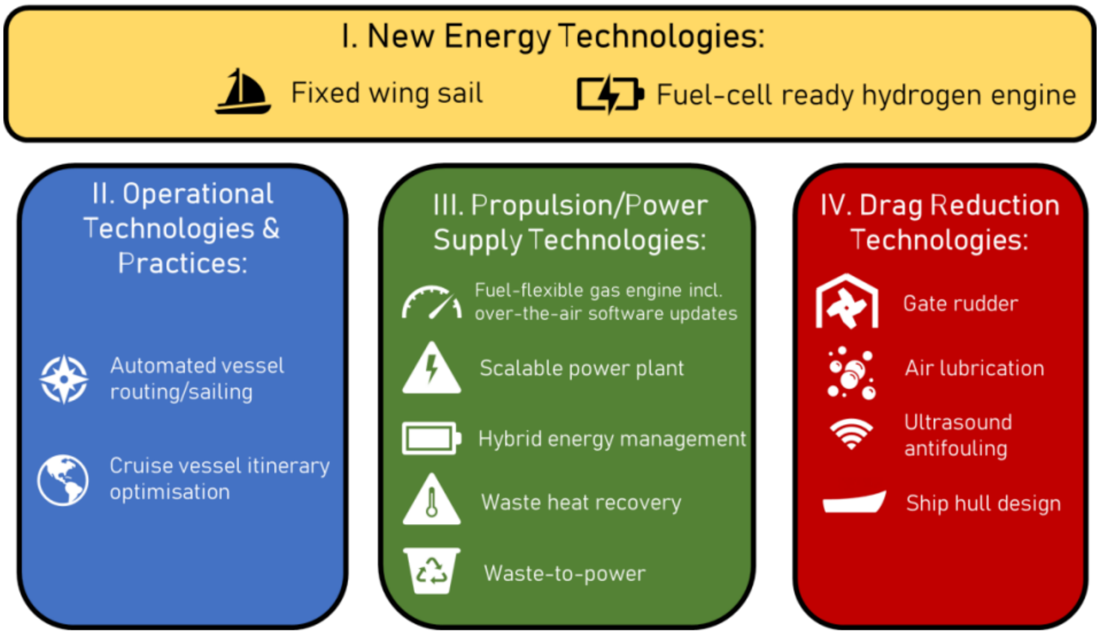

Fig.I.1: Technological synergy for emission savings

From Divers to Robots: Evaluating a Novel System for Underwater Propeller Polishing

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Abstract

This paper presents the performance assessment of a robotic system designed for underwater propeller polishing, a task traditionally performed by divers. The novel robot aims to enhance safety, efficiency, and precision in propeller maintenance. We conducted field trials to evaluate the robot's capability to deliver high-quality polishes with promising results. Key challenges include controlling polishing pressure, dealing with low visibility and attaching the robot robustly to the ship. Results suggest that the robot can polish propellers to at least a similar standard of typical divers, but is challenged significantly if there are factors present that prevent robust attachment, such as obstructing objects close to the propeller.

1. Introduction

Propellers are traditionally polished either by divers or when the ship is in drydock. Hull cleaning robots have entered the hull cleaning market, competing with divers. To our knowledge, no push for robotic propeller polishing, replacing divers, have been successful of yet. There are challenges such a machine must overcome: polishing double-curved surfaces, controlling polishing pressure while floating, lack of depth perception when polishing if only a 2D camera is used, all while dealing with the complexity of a saline underwater environment, with many impact risks (e.g. rope cutters near the propeller). SubBlue Robotics has a novel approach, an ROV carrying a robot arm, a 5 degree of freedom manipulator with a polishing tool as its end-effector. Once the ROV holds itself firm near the propeller, the robotic arm can unfold and move over the surface of the propeller, and press unto it while polishing.

This paper provides a brief description and quality assessment of the propeller polishing robot and the results from polishing so far, based on two case studies, one for a medium size heavily fouled propeller (ca. 5 m diameter, with barnacles), and one for a small lightly fouled propeller (3 m diameter). For an overview on good practice for maintaining propellers, see *Von Rompay (2012)*. The standard way of estimating propeller polish quality is by visual inspection and comparison to a Rupert Scale (using A-F which corresponds to 0,65-32 micron of roughness). For an overview on the impact of roughness on propeller efficiency, see *Mosaad (1986),* which provides some case studies and important theoretical insights from fluid mechanics. In short, a propeller works by having a geometry that leads to a pressure difference between the two sides. Surface quality can impact the propeller’s efficiency either by drag (e.g. high roughness causes drag and energy loss), or by altering the geometry so that the generated pressure difference between the pressure and suction side of the propeller is affected.

2. Propeller Polishing set-up and operation

2.1. System Description

The propeller polishing robot is shown on Fig.1 being lifted into a harbour. A diagram of the robots subcomponents is shown on Fig.2. The core of the technology is an ROV using thrusters to swim from berth to propeller, and a robot arm mounted with a polishing tool. The robot arm is shown in both Fig.1 and Fig.2 having yellow links. The whole robot is remotely operated through an umbilical cable, and the operator controls the robot inside a cockpit in a van.

Once the robot has attached itself near or on the propeller, the robot arm can be unfolded and the operator can control it and polish propeller blades from the cockpit, shown on Figure 3. On Figure 3, the disc can be identified by its bright yellow disc, and polished areas are shown to be clearly shiny compared to areas not polished.

Fig.1: SubBlue Propeller Polishing Robot at harbour

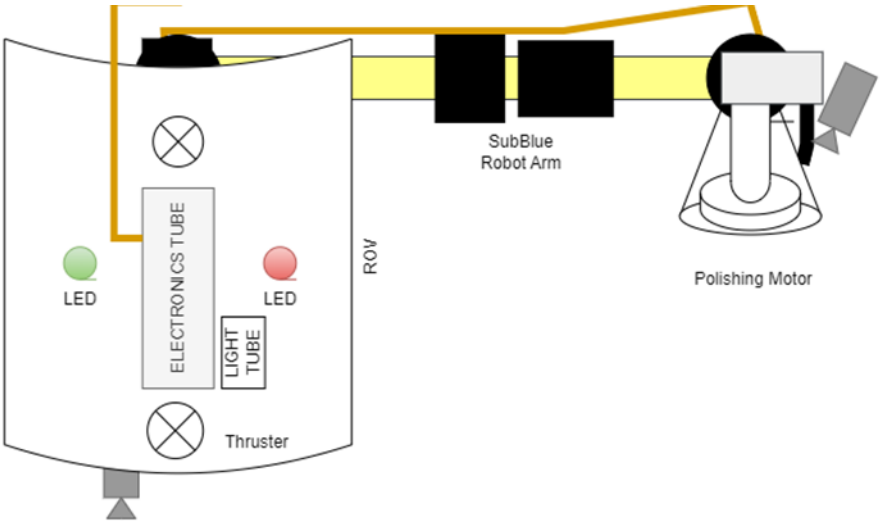

Fig.2: Components of SubBlue Polishing Robot

Fig.3: Polishing of propeller viewed from a) the side and b) operator cockpit

2.2. Polishing Pressure Control

For a diver controlling his polishing disc, he can perceive depth and feel the forces from polishing in his arm. The operator watching on a screen has no depth perception and cannot feel if he is hitting the propeller with the polishing disc at an angle. The robot is designed to control the polishing pressure and orientation, so the operator only must focus on steering motions visible without depth perception.

The polishing pressure control uses conventional force control, the current force measurement is compared with the desired polishing pressure force, and the difference between the two gives the direction and size of the motion increment in the pressing direction, *Spong et al. (2006)*. By using force control, a roughly homogenous polishing pressure can be maintained consistently.

3. Case Study 1: Polishing of Heavily Fouled Medium Size Propeller

Here, the results from the polishing of a 5-bladed 5 m diameter propeller will be presented. It is unknown for how long the propeller had been operating without a polish, but it had spent at least two weeks in the warm waters in Brazil prior the polish, an environment friendly to the growth of fouling. The propeller was heavily fouled with hard barnacles on all blades. The polishing was successful, and a very coarse silicon carbide scrubber was used. Discs finer than the scrubber were destroyed quickly by barnacles.

3.1. Navigating to the propeller

After being lowered into the water, the operator steered the ROV to the propeller, navigating by use of the ship's rudder. Once holding itself firm, the robot can unfold its robot arm to polish, shown on Fig.4. The robot had to be repositioned multiple times to reach both sides of all the propellers blades. For this propeller, proper positioning was very problematic as it had obstructing objects in front of it. Most of the time was spent on navigation and positioning in a way to provide the robot arm with enough reachable area on each propeller blade.

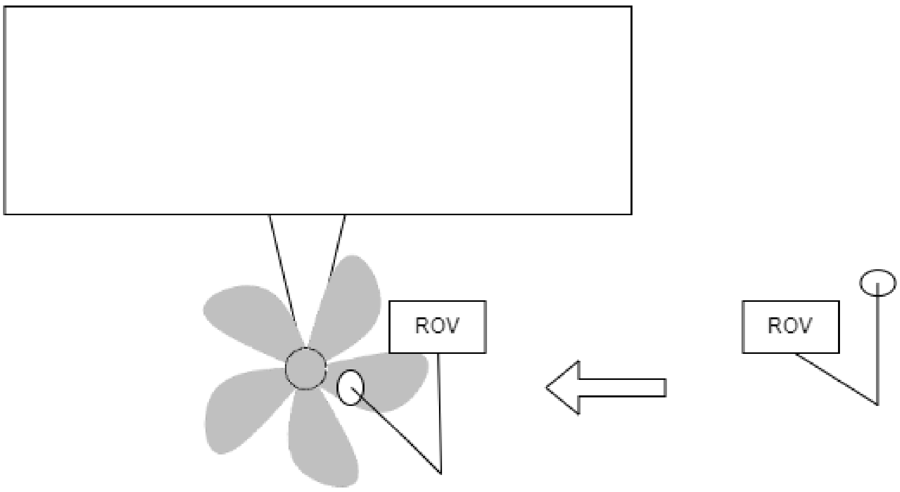

Fig.4: ROV navigation to propeller

3.2. Polishing Results

The typical condition of the propeller blades before polishing is shown on the upper half of Fig.5, this is merely one of the sides of one of the five blades that were polished. The areas closer to the hub had more fouling, and the leading edge had hard barnacles, with lighter fouling (what looks to be grime, slime, corrosive layer) being dominant closer to the tip. After polishing, the propeller blade shines bright, free of barnacles, and reflects light, which it did not before polishing. It should be noted, that around areas with hard fouling and barnacles, the robot arm has polished several times, leaving an irregular pattern revealed by reflective light at those areas. On some parts of the propeller blade was found hard scratch marks, speculated to be from a previous polish with a diamond disc.

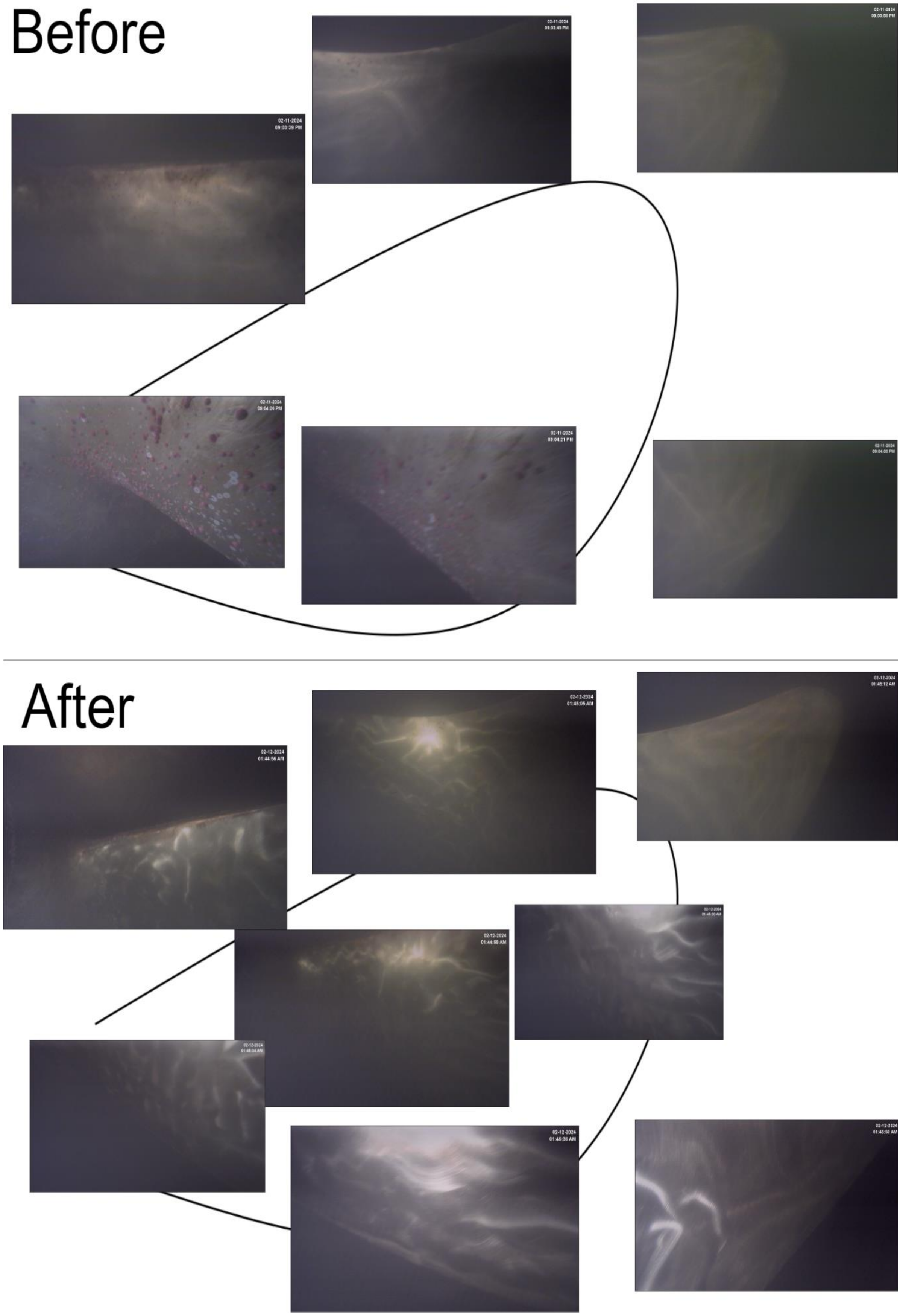

Fig.5: Case Study 1: Heavily Fouled Medium Propeller, before and after polishing

3.3. Conclusion of Case Study 1

This propeller was the first to be polished fully by the SubBlue robot, and showcases that the propeller polishing with robots, without divers, is possible, even for this heavy level of fouling. For this particular propeller, a rough disc had to be used, but if it had been in better condition, a finer disc could have been used. By visual inspection it is not possible to distinguish the polished surfaces from Rupert Scale A.

4. Case Study 2: Polishing of Lightly Fouled Small Propeller

In this chapter, the results from the polishing of a 3 m diameter propeller will be presented. The propeller is a 4-bladed Azimut propeller "Azipull 120" from Kongsberg.

The propeller was lightly fouled from approximately a year in cold waters without a polish. The polishing was successful, and a relatively fine silicon carbide disc was used.

The propeller in question, with its 3 m diameter, is smaller than what the robot was designed for. What this case shows, is that the robot could polish even such a small propeller, and that the polishing with a finer disc leaves a very fine result, what appears from inspection to be Rupert Scale A.

4.1. Navigating to the propeller

Visibility in this harbour was very poor and it was difficult to find the propeller. Once the propeller was found by the ROV it was difficult to navigate the robot arm to the propeller blade by using its own camera, as barely anything could be seen. Also, in this case, the rudder was not visible from the surface of the water, so could not be used to navigate to the propeller.

Poor visibility leading to blind navigation meant that navigation and positioning. still covered more than half of the operational time.

4.2. Polishing Results

The propeller blades were lightly fouled, and more heavily fouled close to the hub. A relatively fine silicon carbide disc was used for this polishing operation and contrasting before/after images are shown on Fig.6. The robot removes the light fouling and leaves a shiny reflective surface, which by visual inspection appears to be Rupert Scale A. Visibility was too poor to show a complete overview of a propeller blade.

4.3. Conclusion from Case Study 2

The robot is fully capable of polishing small propellers. The lightly fouled propeller could be polished by a relatively fine silicon carbide disc, leaving a correspondingly fine result, what appears from inspection to be Rupert Scale A.

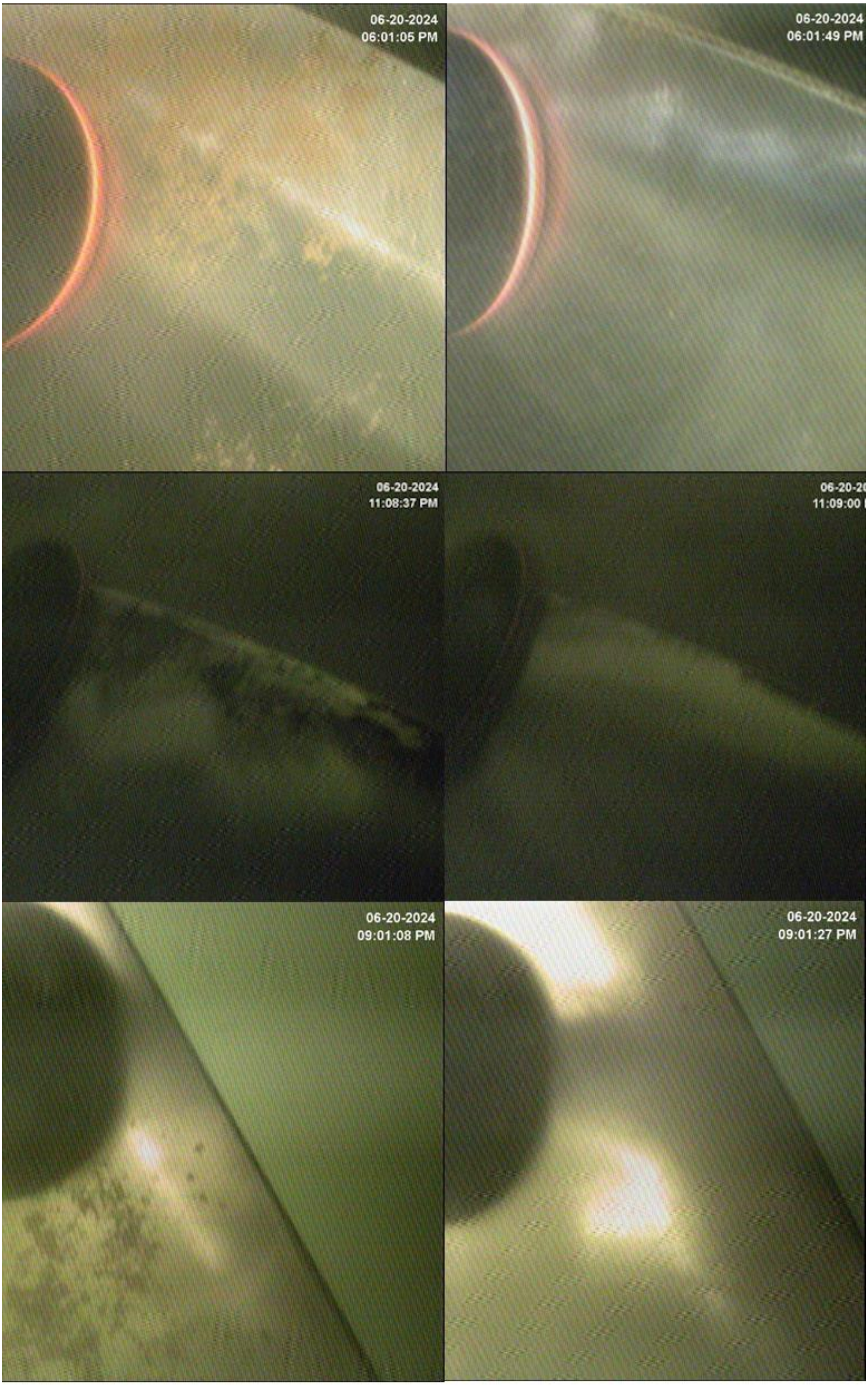

Fig.6: Case Study 2: Lightly Fouled Small Propeller, before and after polishing

5. Quality Assessment and Further Work

The quality assessment of the polishing in the two presented case studies should be understood in the general context of the difficulties assessing polishing quality visually. The visual inspection and comparison to the "Rupert Scale" is an inaccurate method of estimating surface roughness, even when visibility is good, though it is currently the most used practice.

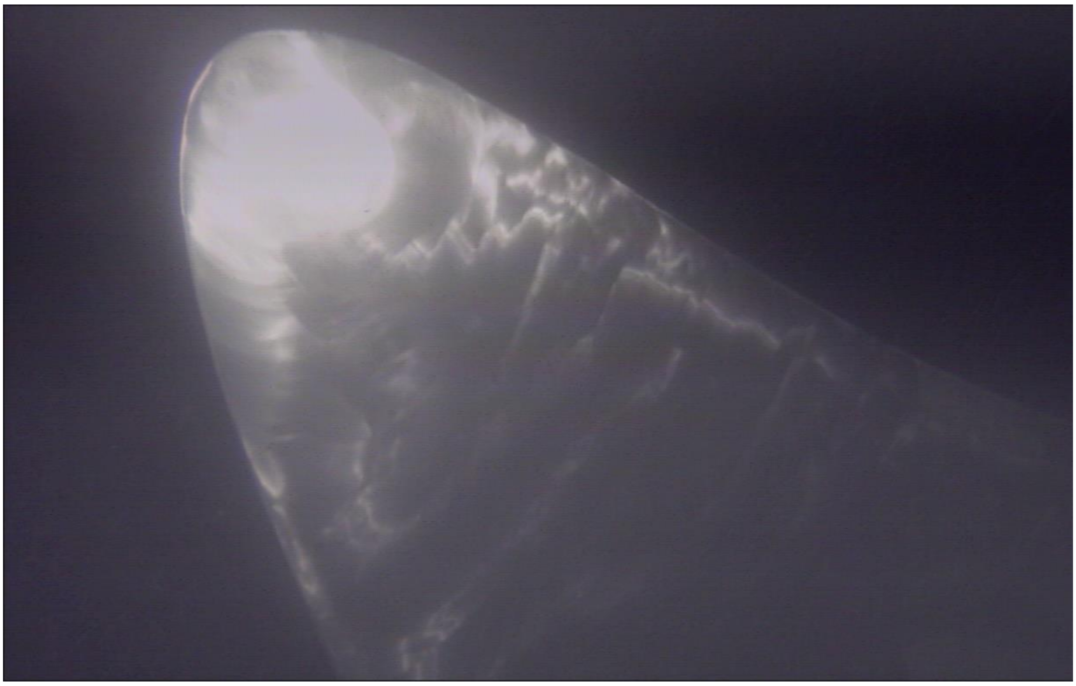

Fig.7: Typical surface condition post-polishing with SubBlue robot, with a silicon carbide scrubber

Polishing propellers with robots has been proven to be possible. This author believes there are perhaps skilled divers that provide higher quality polish, but the quality of polish provided by the robot is on par with the average polish by divers. This author believes the dominant factor in polish quality is the choice of polishing disc, and that poor quality polishing by divers are due to use of diamond discs instead of fine silicon carbide discs. Hence, a multistage polishing would be ideal for any propeller, first polishing hard fouling with a rough disc and then polishing light fouling with a fine disc. For the robot to achieve this, operational time must be reduced. The main challenges to be overcome to reduce operational time are: (1) develop navigation-positioning technique that is robust to poor visibility, and (2) implement a system for swapping between discs while attached to the propeller. Solving these two challenges will make it possible to deliver a consistent multi-stage polishing, the highest quality polish possible.

Acknowledgement

A special thanks go out to David Kofoed from Odin Diving, who was helpful in delivering insights into propeller polishing as a diver and continued helpful counsel whenever asked for.

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Clean Hull Notation: Industry Advancements to Achieve Effective Hull Management

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Abstract

This paper intends to share the experience of the development of the proactive hull management - Clean Hull (CH) Notation. The factors influencing a changing landscape of antifouling coating (AFC) technologies, utilisation and management. Rapid expansion of IWHC technologies and its possible impact on AFC's led to the development of enhanced type approval of AFC. The synergy of energy saving and prevention of transfer of invasive aquatic species (IAS) for a ship using a CH as a notation.

1. Introduction

Biofouling has been identified as a major vector for transfer of invasive aquatic species. Biofouling also has a major impact on the hull/propeller efficiency resulting in higher fuel consumption thus an increase of the operational costs and GHG emissions. Biofouling management has become crucial in present-day shipping and has drawn the attention of the stakeholders such as vessel owners, managers, charterers, local port authorities and various environmental agencies.

Never before has vessel performance been more important than today, as new regional legislation in the form of the EU ETS (Emissions Trading Scheme) and international regulations such as the IMO Carbon Intensity Indicator (CII) rating system come into play, affecting charter party agreements and placing renewed emphasis on efficient operations.

Ensuring the surface of a hull remains as smooth as possible enables a vessel to cut through water with minimal resistance. The less resistance, the less fuel is required to power the vessel, resulting in reduced emissions. It can be argued the performance of AFC's is now part of various regulatory compliances.

Maintaining a clean hull being the objective, in water hull cleaning (IWHC) has become a vital component of vessel operation. Various cleaning technologies and practices are being used to maintain clean hulls.

Consequently, the impact of IWHC on the coating lifespan / efficacy has meant that attention has turned to looked at and ensuring the compatibility of cleaning technology / method to minimize damage to the chosen AFC.

Testing to ensure the compatibility across a range of coating technologies is in the early stages and, with a lack of currently available internationally recognized testing standards, the performance of IWHC devices, in terms of their impact on AFCs has not been verified on a larger scale with a consistent methodology.

2. Antifouling Coatings Systems

We are seeing a "step-change" to industry's approach in hull efficiency and environmental protection and there's been such a seismic shift in thinking. Innovation in terms of what typically would be viewed as hull management has changed quite rapidly and as such AFC manufacturers are adapting new practises.

AFCs fall into some broad types / categories which differ in their chemistry, functionality and their foul deterrence mechanisms. The nature of these differences is important to understand when developing test specification and regimes to assure their compatibility with IWHC devices.

AFC's used in shipping can be divided into 3 major groups: self-polishing copolymers (SPC), elastomeric foul release coatings (FRC) and harder, epoxypolysiloxane based, foul release coatings (HFRC). In this paper we will not consider hard coatings with no foul deterrence mechanism, nor systems utilizing hard, insoluble, non-foul release resin matrixes and biocide.

However, needleless to say hard coating may become preferable option to use with proactive IWHC technologies advocate very frequent hull cleaning /grooming.

2.1. SPC AFC

SPCs are based on specialist acrylic resin technology and in most cases contain inorganic and organic boosting biocides. The biocides are released leaving a very thin leach layer, as the resin matrix hydrolyses and over time will be completely depleted. At this stage the coating will need to be replenished at dry docking which is typically 60 months but can be as long as 90 months.

The SPC can have a range of hardness, achieved by adjusting the basic formulation, allowing for protection of ships with differing activity levels.

When cleaning SPCs the leach layer may be removed resulting in increased foul deterrence efficiencies, however cleaning which is too aggressive may result in too much active coatings being removed and this will shorten the lifecycle of the coating, leading to premature fouling.

SPCs are very prevalent in commercial shipping and are currently believed to account for ~80% of the market.

Note: A new grade of SPC utilising micro-domain technology without the use of biocides is now available and provides initial surface microroughness values which are challenging those of FRC and HFRC.

2.2. Elastomeric Foul Release Coatings

FRCs are based on a silicone elastomer resin matrix, with variations that use functionalised silicone oils and hydrogels to achieve a very low energy surface. The resulting surface, when optimally applied, also has a very low surface roughness which may be ~35% smoother than an optimally applied high end SPC. Reported studies have shown that the SPC coating will also increase in roughness by a much higher percentage per year compared to that for FRC.

The surface properties of FRCs reduce the strength of the adhesive attachment of biofouling and the fouling is released as the vessels speed increases, typically >12 knots.

Although most FRCs are biocide free, there are products which also contain organic boosting biocides which improve their static performance.

Elastomeric systems are by their nature easy to damage but do release adhered fouling with relatively gently cleaning. Using heavily abrasive cleaning methods can however damage the coatings and should be avoided.

2.3. Hard Foul Release Coatings

HFRC, based on combinations of epoxypolysiloxane, graphene and hydrogel technology are relatively new in the commercial shipping sector and currently available through a limited number of suppliers.

They also exhibit a very smooth, low energy surface reducing the strength of the adhesive attachment of biofouling, however they are harder and less easily damaged and therefore can be cleaned with a more abrasive method (nylon brushes for example).

The foul release properties require a higher vessel speed than silicone elastomers but also more easily release fouling using gentle cleaning methods.

3. LR Enhanced AFC Approvals

Although the AFC's, outlined in section 2 above, are formulated and optimised to deter or release fouling during normal operations, the need to maintain a clean hull as part of fuel efficiency, carbon reduction and the prevention of transfer of IAS by making the use of an IWHC is a necessity in most cases. Since IWHC becoming popular, various technologies came into the market. It is therefore required to ensure the compatibility of the IWHC equipment with the AFC.

The industry is responding with initiatives to develop guidance, via IMO, on IWHC and ISO standards to cover methods for performance and documentation of proactive hull cleaning and guidelines for testing such systems. There is however not a widely available coordinated programme, and no currently published standards to assure compatibility, therefore LR have developed a programme in coordination with our coatings customers and their hull cleaning partners, to provide assurance based on evolving test programmes.

AFC's are not certified for their performance. IMO Antifouling Convention provides certification to AFC's assuring no banned substances (biocides) are included in the formulation.

LR enhanced AFC approval aim to ensure the AFC's fit for purpose from its formulation to operation following application on the ship hulls. The enhanced approval process consists of the following:

3.1. Validation of Fouling Deterrence

LR review manufacturer's technology claim of the AFC including test data to validate the efficacy of the product as a fouling deterrent.

For SPC this may include for example polishing rates, biocidal leach rate, raft trial data comparing to positive and negative controls and any hull test patch results during development.

For FRC and HFRC this may include for example data to show that the surface reduces the strength of the adhesive attachment of biofouling, surface energy / coefficient of friction data, raft trial data comparing to positive and negative controls and any hull test patch results during development. Note: Some FRC contain biocides so leach rate data may also be applicable.

Testing as per internationally recognised standards and bespoke methods will be considered as well in-service performance data for established products.

3.2. Verification of Product lifecycle (dry docking / time to recoat)

LR will review data to validate the claims made for product lifecycle / dry docking schedule.

Data to confirm the continued performance as a foul deterrent over the lifecycle may also include for example the polishing and leach rate trial data and also in-service data.

Vessels Biofouling inspection reports, measurement of DFT may be required to be provided.

3.3. Assessment of Compatibility with IWHC Equipment

One of the major concerns of in water hull cleaning is the impact it might have on the coating. If a technology provider claims that their system has no impact, or minimum impact on a particular type of coating that claim needs to be evaluated. This particularly important for hull grooming/ proactive cleaning technologies that advocate high frequency of clean/groom.

AFC manufacturer is to provide the recommended cleaning methods (brushes, water jet, etc.), materials (soft brush, nylon, etc), operations limits (rpm, water pressure, etc) as a part of their technology claim for the AFC.

A test plan is to be developed to assess the impact on the coating. The coating specification and the criteria of assessment should be agreed and confirmed by the coating manufacturer. A set number of repeated cleaning runs needs to be conducted to analyze for example the impact on the topography of the coating specimen and measure thickness, as applicable. Sample water columns for biocides and microplastic as applicable can also provide input to the assessment criteria.

3.4. Verification of operational profiles

Data to be submitted for the continued performance of the AFC including the possible impact from adjacent MGPS systems, ICCP systems.

Proof of continued efficacy post cleaning is an important factor to be considered such as allowable number of cleaning cycles on the stated product lifecycle / dry docking schedule. This would also mean different DFT to be recommended for types of IWHC technologies.

AFC manufacturer also need to provide the intended use in terms of ship operational profiles. Such as recommended vessel types, vessel schedules, place of applications as applicable.

The above testing is evolving, and it is expected that in time internationally recognised test standards and regimes will become available. The need for assurance and guidance in terms of hull management and AFC choices is a pressing need for our shipping partners and the first step towards an assurance in this regard is part of LR's overall strategy encompassed by the Clean Hull Notation.

4. Clean Hull notation as an outset

LR Clean Hull notation provides recognition of of various hull management practices and quantifying it to a surveyable output. As its name stands the intention of the CH notation is to maintain the hull at near cleaned condition at all times.

Clean Hull notation is part of the LR Eco notation category. Eco notation is a voluntary notation assigned for ships which have demonstrated superior environmental compliance. Ships assigned with Eco notations may get subsidiaries from ports, preferential charter rates and higher secondhand value.

LR conduct pre assessment survey to verify the ship designed and constructed to the respective requirements. The ship will also be subjected to an annual survey to verify its operation to the required standards. Ship's AFC should be from a list of coatings that received LR enhanced AFC approval. The MGPS and other niche area protection systems should have their performance verified. IWHC systems should have been approved in accordance with LR Type approval procedure. The service suppliers provide IWHC and Biofouling inspections are from the list of LR Approved service supplier scheme.

Clean Hull notation requires a close relationship with hull management or vessel performance monitoring systems. However, the proactive identification of hull condition is primarily by means of frequent Biofouling inspections. Apart from obvious fuel efficiency gains and reduction of GHG emissions, the CH notation intends to serve as a 'compliance by design' for the requirements beyond 2023 IMO Biofouling guidelines.

Acknowledgement

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An Alternative Multifunctional Strategy for Testing In-Water Cleaning Devices

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Abstract

While full ship trials cannot and should not be fully replaced, in-water cleaning technology developers, coating companies, fleet operators and regulators all have questions that require testing on numerous coating types and using multiple cleaning methods. Addressing these questions using full scale ship tests would be finically and logistically impractical. This leaves information gaps on the compatibility between different cleaning methods and coatings types, and the physical impacts on coating integrity and antifouling performance following an in-water clean. If the shipping industry is to meet IMO guidelines on biofouling management, these information gaps require attention. This paper describes a proven small-scale, multi-purpose test method designed and used for the UK Ministry of Defence, to overcome these challenges and provide answers to a multitude of questions.

1. Introduction

Much discussion & effort has focused on developing a testing protocol for in-water cleaning devices. This has largely focused on in-situ, full scale ship testing requiring complex and costly logistical challenges and typically limited to a single cleaning device and coating type. While full-scale trials will always be required, this paper describes a repeatable, standardised screening test methodology that provides data to fast-track coating and cleaning compatibility for a wide range of cleaning scenarios. This method provides a robust and efficient approach to independently test multiple cleaning or grooming systems on any AFC or substrate, to provide repeatable data describing cleaning efficacy, coating damage, paint particle generation, biocide release and environmental impacts.

2. Background

The requirement for independent testing of in-water cleaning, be that proactive or reactive, is clear to understand. Significant investment for cleaning contracts or the purchase/lease of equipment requires evidence-based data to inform the decision making process. Ever increasing national and state biosecurity regulations demand confidence in cleaning operations. The potential for catastrophic damage to valuable and vital antifoul coating schemes is a very real risk and understanding the compatibility between cleaning systems and coatings, again, requires evidence-based data to inform the decision making process. Not least, some cleaning system manufacturers have also requested some form of standardised and recognised evidence to qualify their own performance claims.

The IMO 2023 "Guidelines for the Control and Management of Ship's Biofouling to Minimise the Transfer of Invasive Aquatic Species" (hereafter referred to as The Guidelines) clearly states that "The choice of AFC should be compatible with the cleaning technologies available to ensure both minimum biofouling growth as well as reducing the risk of damage to the AFC and the potential release of harmful waste substances to the environment". Specifically, the Guidelines advise that:

- AFC manufacturers should provide guidance on cleaning frequencies and suitable methods,
- In-water cleaning service providers and manufacturers should provide guidance on AFC compatibility,
- End users should consider what cleaning technologies are available to them and therefore, choose AFCs that are compatible with those technologies.

The Guidelines do not state how this guidance or compatibility choice should be informed and so a knowledge gap has been created.

BIMCO have made enormous progress in the development of an industry standard and approvals procedure for cleaning with capture systems, with valuable input from many in the industry and academia. The challenge to qualifying in-water cleaning efficacy is considerable and not to be underestimated, as are the logistical challenges of conducting such trials in a repeatable and comparable manner. The logistical and financial challenges are often difficult to overcome. The end result of a successful industry standard test, however, is data for one clean, of one coating, at one level of fouling, for one cleaning system, and of course, this needs to be repeated on three separate vessels.

While testing of this kind will always be required, if it's not optimised, there is great potential for this full-scale testing approach to consume large amounts of time and resource. Given the logistical challenges of securing access to vessels in the required geographic location, with the required level of fouling, with the required coating type, generating sufficient data to fully describe the ever increasing range of cleaning technologies and coating types will be not only expensive, but very time consuming.

There are still, many unanswered questions and many testing outputs required by developers, operators, end users, coating companies and regulators. These include:

- The question of compatibility between cleaning systems and coating systems, identified by the IMO Guidelines. This is not a question that can be answered easily or efficiently using single ship trials. Many companies or organizations have a requirement to find the best cleaning and coating combinations for a range of operational profiles, or to understand the effects of a cleaning technology on a range of potential coating systems, or indeed, how coatings react to different cleaning methods.
- No system can guarantee 100% capture and most proactive systems, with logical reasoning, do not attempt to do this. However, this leaves regulators with difficult decisions between prohibiting the generation of any deposit to the seabed, against leaving an infested vessel in-situ and essentially permitting the spawning of potentially invasive non-native species on a daily basis, not to mention the damage to the vessels operational efficiency and increased greenhouse gas emissions on her next passage.

If evidenced based data were available, not only describing the effects of those cleaning systems on a wide range of coating schemes, but also the direct effect of paint particles on the marine environment, regulators and decision makers would have the option for an alternative response to a cleaning request, other than "do nothing" and the IMO Guidelines could be implemented.

3. Small-Scale Test Set-Up

The use of an in-service vessel, even one with coating patch tests in place, to carry out in-situ, full-scale tests on multiple cleaning systems and multiple coatings is logistically and financially impractical.

The use of scaled down test panels and scaled down cleaning units provides a practical solution for complex trials involving multiple test subjects. This scaled down approach can be used to ensure that the considerable time and energy required to conduct a full-scale test is only used once basic questions of coating and cleaning systems compatibility have been addressed and to ensure that maximum benefit from the full-scale test is achieved. In this sense, the small-scale approach described here can be considered as a screening exercise to ensure that only full-scale tests with the highest chance of producing useful data are conducted, saving the industry and regulators time and money.

The set-up for such a small-scale trial broadly involves the following:

- **Small-scale cleaning substrate / test panels:** 600 mm X 600 mm X 5 mm mild steel panels, professionally prepared and coated with complete AFC systems to the manufacturer specifications.

- **Small-scale cleaning systems:** to date, tested systems include **ECOSubSea, Hydro Hull Cleaning** and **Greensea IQ** who have all kindly provided single or reduced head cleaning systems for use in the trials, and also the **Mini Pamper** brush system (commercially available).
- **Multiple Antifoul Coatings:** to date, tested coating systems have kindly been provided by six leading coating manufacturers.
- **Panel Pre-treatment -** pretreatment of the panels ensures that any required level of fouling (clean, biofilm only, weed, invertebrates) are present of the test panels at the required level.
- **Bespoke Test Rig:** in-house engineer designed bespoke rigs to house each unique cleaning system. These rigs hold the cleaning device in place and facilitate the controlled and repeatable travel of the cleaning system across the test panel which is housed on the base of the rig, while ensuring that each cleaning device is able to operate as designed by the manufacture
- **Professional Hull Cleaning Operatives Onsite –** experienced in-water cleaning divers and cleaning technology developers on site to support and advise to ensure that the clean is as representative as possible.
- **Test tank:** various sizes of tank can be used, each suited to different cleaning systems, with a current maximum capacity of 3750 litres.

Fig.1: Test rig fitted with small-scale cleaning device and test panel being lowered into tank for test clean

Prior to the cleaning trial, newly coated test panels are leached to remove volatile organic compounds, soften the coatings as required, and expose them to natural biofouling. Control panels are deployed alongside test panels, both positive and negative, and all with a minimum of three replicates. Fouling pressure in this location is seasonal (~April to October) but high, including a wide range of calcareous and soft fouling species and several non-native species, some of which are known to have a level of copper tolerance. Currently, deployment is static but dynamic options are under development. Testing can be carried out at any specified time period after deployment, depending on the client requirements. Typically, the highest performing coatings will only develop a light biofilm over a single season where as the negative control will be <100% fouled with calcareous and soft fouling organisms in a matter of weeks.

Fig.2: Two post-clean panels where top sections have been cleaned, left showing high performing coating after a proactive clean, right showing a heavily fouled negative control panel after a reactive clean.

The precleaning assessment includes photographs and physical assessments of the level of fouling (LoF), dry film thickness (DFT), surface roughness and coating damage. The panel is then placed and secured on to the test rig which is also fitted with the designated cleaning system, and the entire rig is hoisted in to the test tank. At this point the cleaning system is located off the panel to avoid any contact before the test cleaning run. When all systems are ready, the cleaning run commences. Cleaning run times are calculated to mimic real contact times of in-field cleans; typically a matter of seconds. The cleaning run ends with the cleaning system off the panel.

After the cleaning run is complete, five litre water samples are taken, the panel is removed and post clean assessments are carried out before the tank, rig and cleaning system are thoroughly pressure washed clean. Control water samples are taken throughout to verify that cross contamination does not occur between cleans.

Table I: Non-exhaustive list of standard small-scale IWC test categories

TEST CATAGORIES	TEST TYPE	DETAILS
Coating Tests	Cleaning Efficacy	Level of fouling (LoF) pre and post cleaning, calcareous base plate and other biological remains post cleaning
	Physical Damage	Track marks, spiralling, chips, gouges, scratches etc
	Coating Properties	i) Dry film thickness, ii) surface roughness & iii) contact angle changes
Waste Water Tests	Released material from AFC	i) Antifoul paint particles, ii) biocides & iii) biological debris
	Ecotoxicological Impacts	Toxicity of particles on marine organisms
General Test Questions	Comparative effects of various pressures/brushes/speeds and/or LoFs	
	Comparative effects of multiple recleaning events	
	Comparison of Cleaning Methods on Each AFC	

4. Test Questions

Multiple tests can be carried out on the test coatings and post cleaning water and general questions can be answered using this approach. Standard test questions are shown in Table I but the opportunity to present additional questions is clearly available.

5. Limitations

The small-scale test methodology does have limitations, some of which are discussed below:

- Panels are flat mild steel sections, with no weld lines or areas of coating or corrosion failure and the surface area for cleaning is limited. While the panels adequately represent the vast majority of the cleaning area, curvature and irregularities have not yet been investigated. Larger panels including weld lines or curved structures could be considered if required.
- The small-scale cleaning devices in our test facility do not have to deal with varying environmental challenges such as high tidal flow and low visibility. These variables would be more suited for testing on a full-scale ship trial.
- Experimentally, the data are also somewhat limited due to the reduced surface areas involved and scaled-down units, without wheels/tracks. For this reason, data should be treated as "best case scenario" data and any selected combinations should always undergo full scale trials. Generally, however, poor performing combinations of coating and device at this scale can be considered non-viable.
- This test method only addresses the cleaning system and is not designed to test filtration systems. However, PML Applications has also designed a full BIMCO style field test for full ship tests which includes filtration testing along with efficacy, capture and water quality.

6. The Benefits

While there are acknowledged limitations of a small-scale trial, many benefits are also clear, some of which are discussed below:

- Tests are carried out in a controlled, scientifically robust, repeatable manner that produces quality independent and impartial data.
- Tests offer the capability to perform head-to-head trials of cleaning systems (e.g. brush verses HP water jet, reactive versus proactive etc) with a standardised, repeatable and cost-effective method.
- This approach provides the opportunity to test multiple parameters including different settings on the cleaning device such as speed and pressure, and can also extend testing to refouling trials and/or answer follow-on questions. After initial CAPEX, panels are available to continue a variety of testing for several years.
- Data are gathered in a relatively short time frame after the deployment period, providing useable, and insightful information within commercially relevant time scales.
- The complex logistics of testing multiple coating and/or cleaning systems are all devolved to the test house.

7. Future Potential

This paper introduces the small-scale cleaning trials carried out to date. Future investigations are outlined below:

- Long term refouling trials to understand the effect of repeated cleaning.
- Optimal cleaning interval trials.
- Larger, more complex substrates with full-scale cleaning systems.

8. Discussion

This test method has been developed over 2023 and 2024, initiated by the UK Ministry of Defence to test cleaning and coating systems for its surface ships. Proactive cleaning company, Greensea IQ, have carried out their first set of trials testing against standard brush system and are at the beginning of their second set of trials focusing on copper. ECOSubSea, Hydro Hull Clean and Greensea IQ have all been involved in various trials. Data from these trials have been used to provide evidence to regulators who up until now have only had access to sparce data to inform an IWC policy. These trials clearly have limitations when compared to BIMCO IWC trials, which they are not designed to replace. Instead, this method provides a complimentary approach which if used prior to full scale testing, can help ensure that only the most useful and informative full-scale trials are conducted, saving the industry and regulators time and money, and informing several important knowledge gaps regarding in-water cleaning as rapidly as possible.

Acknowledgements

PML Applications would like to thank all those companies involved in the trials to date, especially the Defence, Equipment & Support (DE&S) department of the UK Ministry of Defence who were instrumental in the initial development of these trials. Also, thanks go to the early adopters of this method for their continued support and drive that continues to expand its potential, in particular Greensea IQ. Our thanks and gratitude to EcoSubSea and Hydro Hull Clean who both supplied small-scale cleaning devices to us in Plymouth UK and provided the support to run them properly. Also to the coating manufacturers who offered their coatings and allowed us to test them. Lastly, our thanks go to Mr Rob Horton-Howe, owner of Augean Divers Ltd, who bought a wealth of experience and knowledge to these trials from the start and ensured that they were designed and executed as close to real-world scenarios as possible.

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Copper Release Rates under Static Conditions along a Salinity Gradient

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Abstract

A new field test method is presented, which is more robust and less resource demanding than current methods. Painted panels were immersed at mooring sites all over Europe, representing both Baltic, Baltic transition, Atlantic and Mediterranean waters, with salinity levels ranging from 3 to 38 ‰. The release rate was determined with optical microscopy and verified with chemical analysis. The results confirmed that the copper release rate slows down when vessels are laying idle. Furthermore, the salinity had less influence on the copper release rate than previously anticipated. The study was conducted on antifouling paints for pleasure crafts moored in marinas, but the methodology and the test results are transferrable to merchant vessels laying idle in ports and harbours.

1. Introduction

When conducting risk assessment of antifouling paints, it is necessary to determine the release of the biocides and substances of concern, like copper and zinc from Cu2O, CuSCN and ZnO. Under the EU-BPR (EU biocides products regulation), it is of particular importance to measure the release rate from pleasure crafts when moored inside closed marinas. In the future, similar documentation is expected to be required in ports and harbours.

The US Navy Dome method, *Seligman and Neumeister (1983),* is the only available recognized method for direct in situ measurement of copper release from the hulls of moored vessels. The method is expensive, impractical for routine use and difficult to standardize.

There are ASTM and ISO standards available based on laboratory experiments. However, after two round-robin tests, it was found that the inter-lab and intra-lab variations were high and concluded that the results of these standards were not suitable for direct use in risk assessments.

The ISO 10890 Mass balance calculation method was developed as a response to this, to give conservative estimates for the total release over the lifetime of the product. The underlying principle is that a paint cannot release more biocide than was present in the paint when applied. However, when a boat is moored, the ISO 10890 method will strongly overestimate the release rate, typically by approximately 3x versus the US Navy Dome. *Finnie (2006)* developed correction factors to improve the estimates of environmental copper release under mooring conditions.

These correction factors have been challenged by *Lagerström et al. (2020).* They developed a method with direct measurement of the metal content on painted small plastic panels, before and after seawater immersion, using a portable XRF instrument. The testing has been limited to short term exposure of thin films in Swedish waters.

2. Materials and methods

2.1. Test set-up

A number of antifouling paints were evaluated representing different technologies with regards to binders and biocides (Cuprous oxide and Cuprous thiocyanate). Each paint was applied in triplicate using a draw down bar applicator directly to a PVC panel (105x32 cm) that had previously been abraded with P120 sandpaper and primed (Vinyl Primer, 1x40 µm DFT) to provide test strips, each of nominal size 5 x 15 cm with an average dry film thickness of approximately 50 µm. The PVC panel was attached to a steel frame adding up to a total weight of 8 kg. The side-to-side spacing between adjacent painted test strips in the array was typically about 2 cm and the end-to-end spacing between rows was about 2 cm. A coat of SeaQuantum Ultra S was brush-applied to the edges and back of the PVC panel and to the area between the painted test strips to protect them from biofouling during the test. Non-polishing reference marks were applied to the surface of the painted test strips in the form of three 3 cm long strips of a white non-polishing antifouling paint (Racing White) and each painted test strip was uniquely numbered for identification purposes with the same non-polishing antifouling paint.

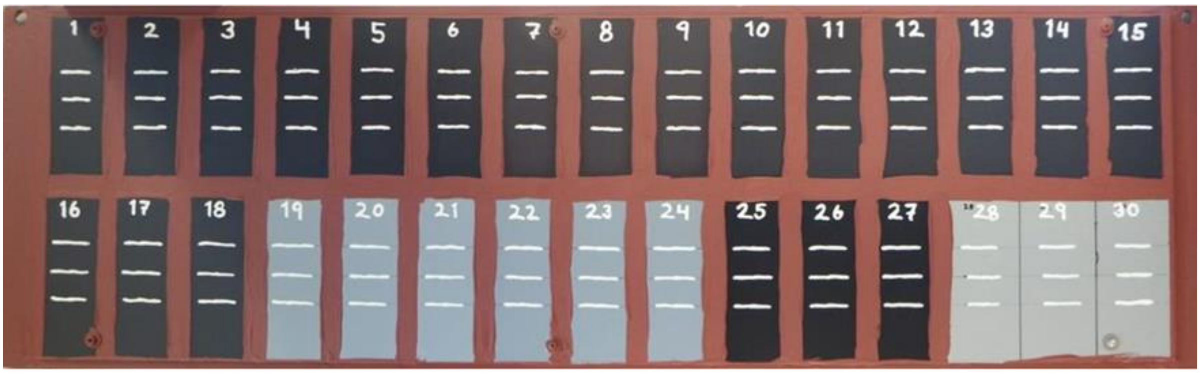

Fig.1: Closed panel array used in Field test 2 where triplicate test panels of each test paint were applied to a PVC board that was attached to a steel frame.

At each test site, the panel array was hung vertically from a floating jetty alongside moored pleasure craft and permanently immersed at a depth of 30-50 cm below the water surface. After exposure, the panel arrays were retrieved and the actual number of days of exposure at each study site was calculated.

2.2. Copper release rate test protocol

An approximately 1 x 7 cm sample containing a section of non-polishing reference mark and adjacent exposed test paint was cut from each retrieved panel using a bandsaw and embedded in clear epoxy resin and examined in cross-section with an optical microscope using image analysis software in order to determine (a) the thickness of the coating under the non-polishing reference mark (DFT0) and (b) the thickness of the unleached copper oxide in the adjacent exposed portion of the test paint (DFTx, where x is the exposure period in days). In each case, the determined thickness was taken as the arithmetic mean of 6 measurements. The mean copper leaching rate ($\mu g \cdot cm^{-2} \cdot day^{-1}$) over the exposure period was calculated according to the ISO 10890 method, *ISO (2010).*

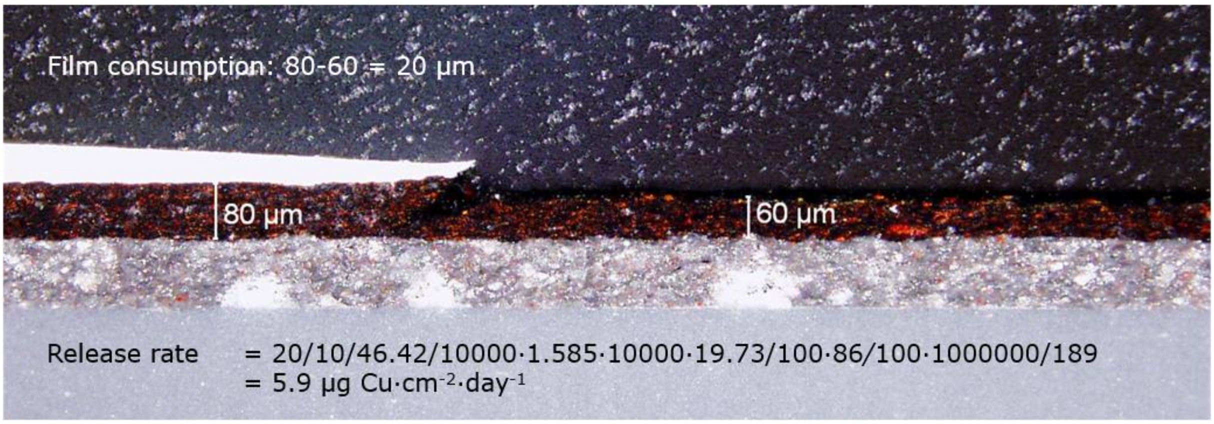

Fig.2: Cross-cut section of a paint film after immersion in seawater as seen in the optical microscope where DFT_0 = 80 µm and DFT_{189} = 60 µm in this case

$R_{Cu} = (DFT_0 – DFT_x) \cdot 100/VS/10000 \cdot \rho \cdot Wa/100 \cdot a \cdot 1000000/\text{Exposure period}$

DFT_0 = average dry film thickness of unexposed paint under the non-polishing reference strip; DFT_x = average dry film thickness of the intact copper oxide layer after exposure for x days; VS = Volume solids content (in % by volume); ρ = Density of the wet paint (in kg dm^{-3}); Wa = content of biocidal ingredient in paint formulation (in % by mass); a = Mass fraction of biocide in the biocidal ingredient; Exposure period = the number of days the panel had been immersed at the test site.

2.3. Field study 1

A preliminary field study was undertaken in order to demonstrate the utility of the release rate method and to investigate the effect of the exposure conditions on the in situ copper release rate. The study involved quantification of the copper release rate from 6 antifouling paints that were immersed over a 12-month period (June 2020 – May 2021) at two enclosed marinas for recreational crafts located in southeast coast of Norway on the Skagerrak: Vadskjæret marina, Larvik, Norway (TS1) and Stavern marina, Stavern, Norway (TS2), Fig.3.

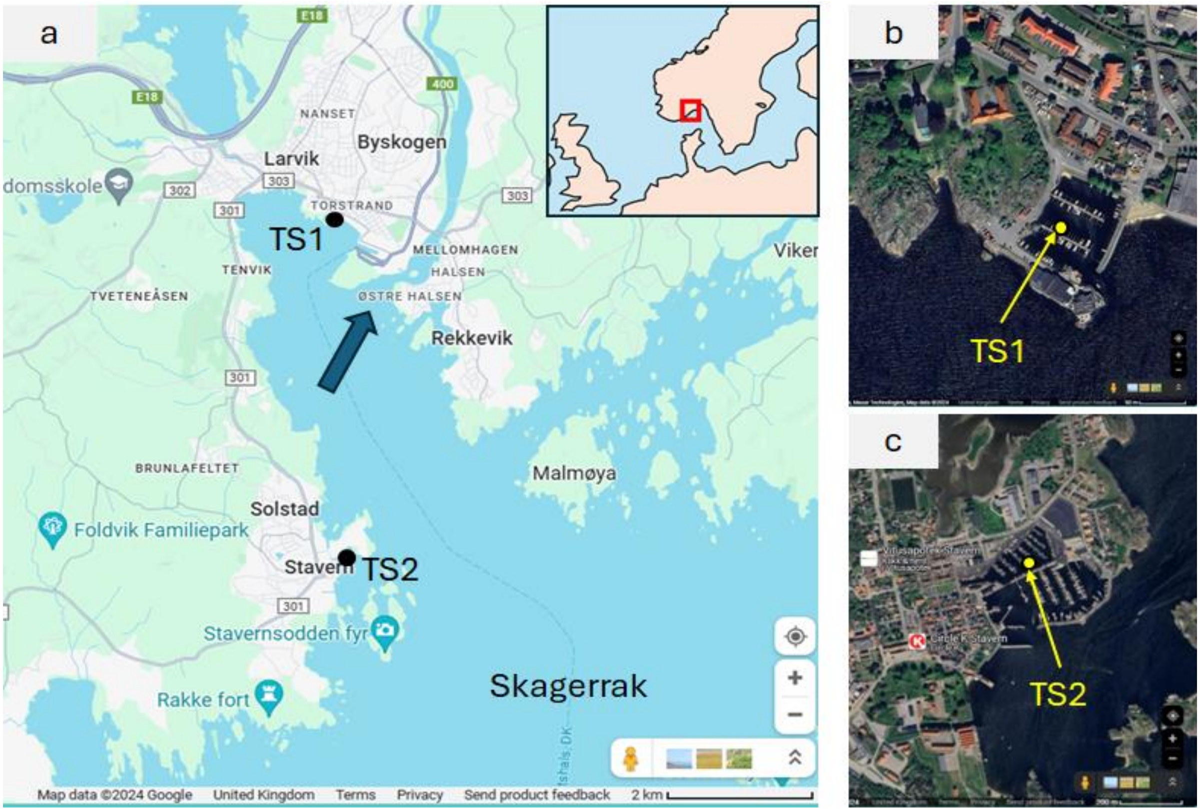

Fig.3: Google maps images showing (a) the general locations of the test sites at Vadskjæret marina, Larvik (TS1), Stavern marina, Stavern (TS2) and the mouth of the Numedalslågen river (blue arrow); (b) and (c) satellite images showing the locus of exposure at each test site.

2.4. Field study 2

A second field study was undertaken to more widely investigate the effect of the exposure conditions on the in-situ copper release rate, where the exposure locations were selected to more widely exemplify the range of exposure conditions encountered across the European continent. The study involved quantification of the copper release rate from 9 antifouling paints that were immersed over a 6 month period (April – October 2021) at five European marinas for recreational craft: Stavern marina, Stavern, Norway (TS2); Östervik, Stockholm, Sweden (TS3); Sjöstadens Varv marina, Gothenburg, Sweden (TS4); Yatesport marina, Vigo, Spain (TS5); and Club Nautic L'Escala, Girona, Spain (TS6), Fig.4.

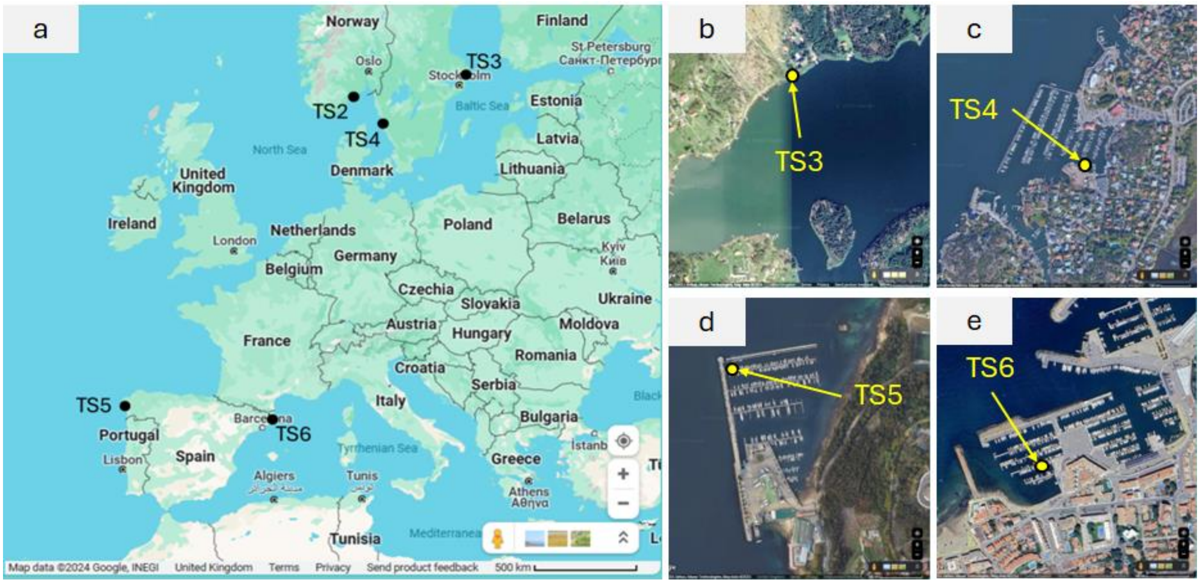

Fig.4: Google Maps showing (a) the general locations of the test sites at Stavern marina, Stavern, Norway (TS2); Östervik, Stockholm, Sweden (TS3); Sjöstadens Varv marina, Gothenburg, Sweden (TS4); Yatesport marina, Vigo, Spain (TS5); and Club Nautic L'Escala marina, Girona, Spain (TS6); (b)-(e) satellite images showing the locus of exposure at each test site.

3. Results

First, a preliminary field study was undertaken in order to demonstrate the utility of the release rate method and to investigate the effect of the salinity on the in-situ copper release rate. A second field study was undertaken to more widely investigate the effect of the exposure conditions on the in situ copper release rate, where the exposure locations were selected to more widely exemplify the range of exposure conditions encountered across the European continent.

3.1. Field study 1

The leaching rates of copper have been determined by static exposure inside two Norwegian marinas with different oceanographic conditions. Panels with 6 paints (A-F) were immersed for 4, 6 and 12 months before removal and analysis of leaching. The copper leaching rates were calculated based on the measured Film consumption.

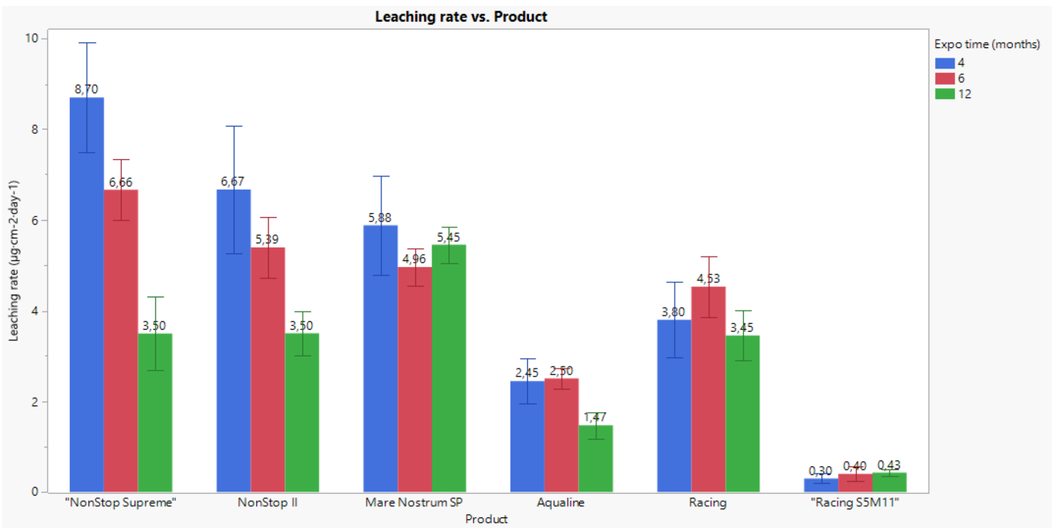

Fig.5: Illustration of the average copper leaching rates for the antifouling paints after four, six and twelve months static exposure.

The release rate slowed down during exposure, and after 12 months the rate was 2.8 times lower than the calculated value according to ISO 10890, *ISO (2010)*. The difference in leaching rate between the two sites was not significant, even though the difference in salinity was 10 units.

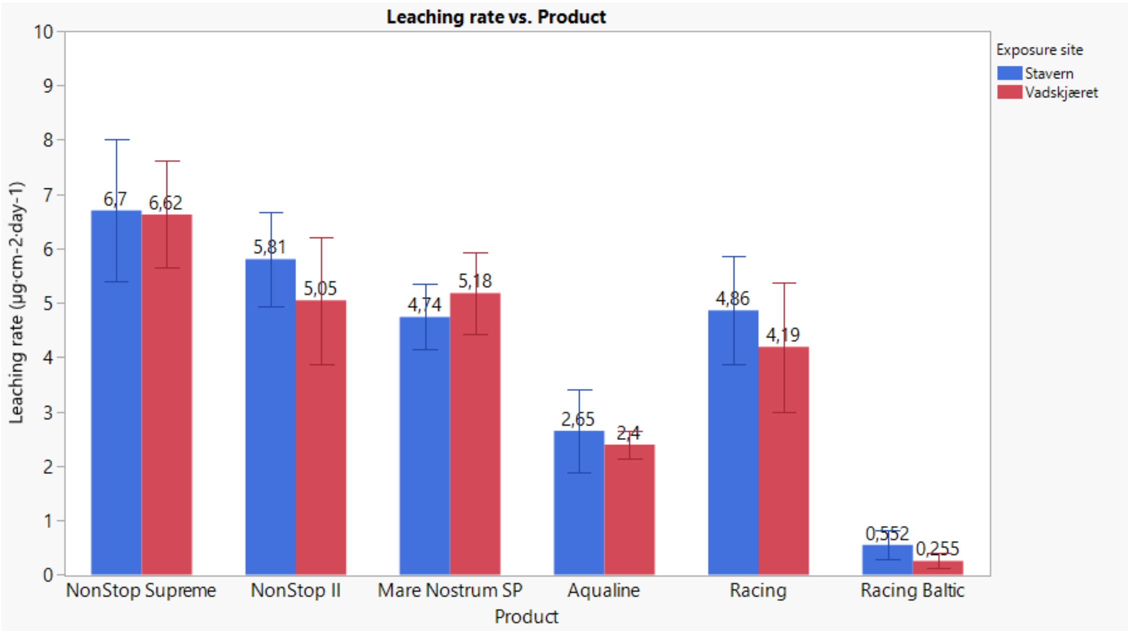

Fig.6: Average copper leaching rates for antifouling paints at Stavern (23‰) and Vadskjæret (13‰)

3.2. Field study 2

The leaching rates of copper have been determined by static exposure at five different European sites with different oceanographic conditions. Panels with triplicate stripes of 9 paints (P1-P9) were immersed for 6 months before removal and analysis of leaching.

One of the products, P5, has previously been reported to increase the copper leaching rate significantly with increasing salinity, *Lagerström et al. (2020)*. This was clearly not the case in this study.

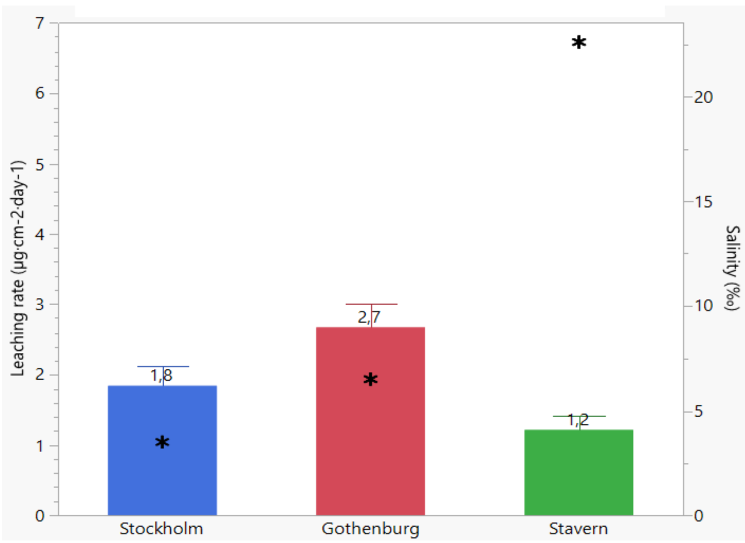

Fig.7: Copper leaching rates for antifouling paints P5 at three different test sites (Stockholm, Gothenburg and Stavern) with different salinities and similar temperature

Looking at the combined results, an average of all the 9 products tested at each site, the leaching rate in Spain, with higher seawater temperature and salinity, is higher than in Scandinavia. However, the leaching rate in Stavern is lower than Gothenburg even though the salinity is higher and the temperature similar. Same with Girona and Vigo. Apparently, other parameters than the salinity are influencing the leaching rate. From investigations of the test sites, it was clear that the seawater flow/exchange rate had a greater impact than the salinity.

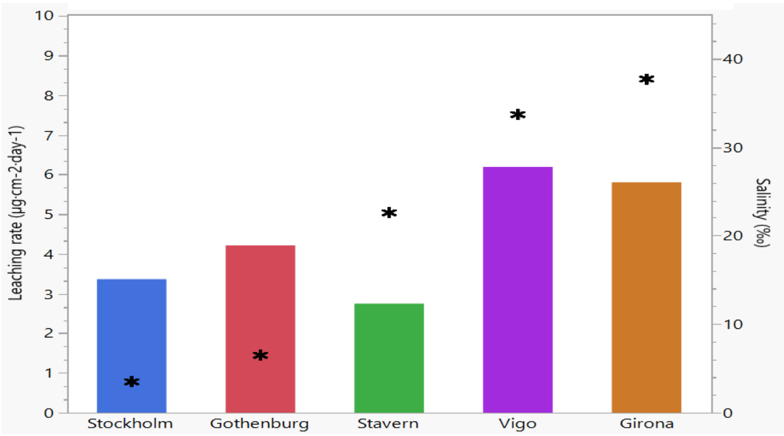

Fig.8: Average copper leaching rates for the 9 antifouling paints at five different test sites (Stockholm, Gothenburg, Stavern, Vigo and Girona) along a salinity gradient

3.3. Chemical analysis

The microscopy method used to measure the leaching rates was validated by chemical analysis of metal components left in the exposed paint film. Elemental copper and zinc in the samples were analyzed externally using ICP-OES (Inductively Coupled Plasma - Light Emission Spectrometry). Two parallel samples from each test stripe were analysed (A and B). The differences in the results with the two methods are small and linked to the inherent uncertainty in the methods used.

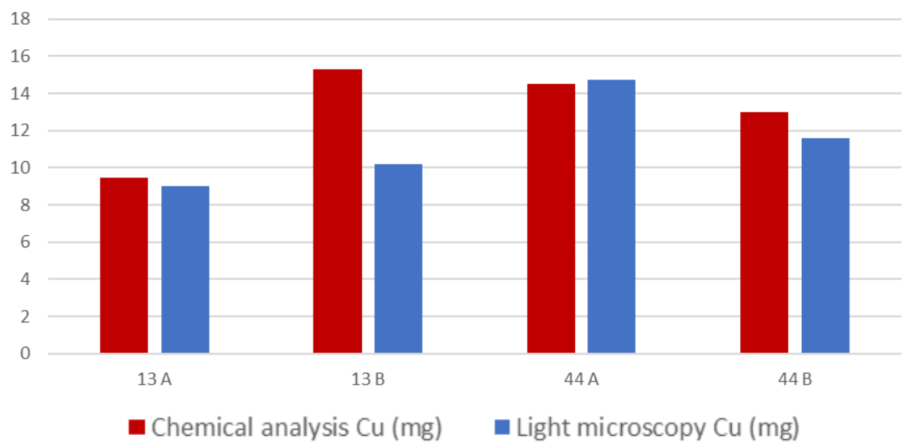

Fig.9: Results from chemical analysis and light microscopy used to determine the quantity of copper left in the exposed paint film of test paints P5 (panel 13 exposed in Stockholm and 44 in Gothenburg)

4. Conclusions

The copper release is slower when the boat is laying idle inside a sheltered marina. Hence, correction factors should be used to improve the estimates of environmental copper release under mooring conditions.

The seawater flow has a greater impact on the release rate than the salinity.

Microscopy is an easy method to use and gives an accurate measure of the copper release rate.

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In-water Monitoring with 3D Reconstruction and Acoustic Biofouling Detection

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Abstract

Subdron offers a pioneering solution for underwater inspection using autonomous underwater vehicles to collect high-resolution data in low-visibility waters. The technology includes underwater localisation for safe navigation in confined spaces, 3D scanning, biofouling detection using acoustic sensors, and data processing to create a 3D asset model and automatically identify potential problems. This solution benefits port authorities by enhancing underwater asset monitoring and digitalising infrastructure while providing ship owners with accurate hull assessments and biofouling maps. Subdron's services improve monitoring efficiency and reduce costs, offering higher-quality hull monitoring in a shorter time and at a lower cost.

1. Introduction

Structures submerged in water are exposed to forces that quickly reduce their operational efficiency. The effects of saltwater lead to corrosion, while materials that accumulate on surfaces result in deterioration and reduced effectiveness. Therefore, it is of utmost importance to conduct close-up inspections to identify cleaning, repair, and maintenance needs. Currently, most underwater inspections are performed by divers using visual or sonar cameras. However, this manual approach has several pain points.

Commercial inspection companies - face the following pain points:

- Manoeuvring in confined spaces increases the risks of accidents and equipment failure potentially putting the entire dive team at risk.
- Poor visibility as little as 50-3cm: Divers rely on visual cues to navigate the inspection area. Knowing one's exact location in respect with the structure inspected is crucial. Also, poor visibility means divers are not able to see potential hazards.
- Non-positional video footage makes assessing, monitoring, and tracking identified anomalies for an action plan difficult

The number of fatalities and serious injuries is a real concern for inspection companies. To ensure basic diver safety each inspection team needs to have 1-2 rescue divers on topside. This increases the costs of each inspection.

Maritime Shipping companies and authorities in general face the following pain points:

- Cost of €7,000-€12,000 per inspection
- Significant downtime needed for routine inspection.
- Lack of recurring and easy to interpret data that automatically shows the degree of severity. This makes decision-making difficult and predictive maintenance impossible.

Inspection is key for Maritime Shipping companies, with regular inspection they can detect and reduce the biofouling on naval vessels. Biofouling increases vessel drag and thus fuel consumption. This has a direct impact on GHG emissions. The US maritime shipping industry estimates biofouling increases shipping costs by €36B per year, *Sofar Ocean (2024)*. Moreover, some organisms of the biofouling can be invasive species which can enter in the environment with the vessel. Biofouling must be effectively addressed to decarbonize the shipping industry, reduce costs, and prevent the spread of invasive species, *IMO (2023)*. To achieve this, ship operators need to accurately identify the location and extent of biofouling accumulation to initiate cost-effective and proactive cleaning measures.

In addition to biofouling, underwater inspections are vital for detecting damage to ship parts like a propeller, which can affect operational efficiency and pose a safety hazard. Alternatively, leaking stern tubes, broken thruster tunnels, clogged sea chest grids, damaged bilge keels and hull cracks can lead to costly repairs and environmental pollution if left undetected.

Port authorities must conduct regular inspections of port infrastructures to monitor the condition of different elements, ensure the safety of the infrastructure, and take preventive actions to extend its lifespan. For instance, ports are currently facing challenges due to larger and more powerful ship thrusters, which create high flow velocities against quay walls, sheet pile walls, and the harbour basin bottom in front of the walls. As a result, harbour bottoms that were not designed for these extreme velocities may experience increased erosion and potential wall failure, *ATPyC (2018)*. Additionally, many port authorities are in the process of digitalizing port operations and subsystems, making the creation of a digital twin of their infrastructure essential.

Recently, underwater vehicles such as Remotely Operated Vehicles (ROVs) and Autonomous Underwater Vehicles (AUVs) are being used to support divers in underwater inspections. ROVs require a highly specialized crew and support equipment on the surface (control station, tether, and winch) throughout the operation. ROVs can achieve comparable results to a diver without putting humans at risk, but they still lack positional information and are limited by water conditions and tether management in complex areas. On the other hand, AUVs typically rely on Global Navigation Satellite System (GNSS) systems and dead reckoning to navigate in open waters. Still, this approach is unsuitable for the confined spaces required for underwater inspections.

Subdron is the first to introduce a revolutionary end-to-end autonomous underwater inspection solution. It is the only solution for safely navigating confined environments while collecting accurate data. The solution is composed of an underwater navigation algorithm, a data cloud that automatically reconstructs the inspected area in 3D, detecting anomalies and biofouling, and a user platform that allows end users to visualize and explore the data.

2. Subdron's Autonomous Solution for Underwater Inspection

For the first time, Subdron's solution covers the entire underwater inspection process, from data collection to processing and sharing. As pictured in Fig.1, our proprietary solution consists of 3 main parts. First, safe navigation and robust positioning for any commercially available underwater robot; second, data processing and labelling of complex data using machine learning to identify crucial anomalies; and third, an easy-to-understand visualization of the critical infrastructure.

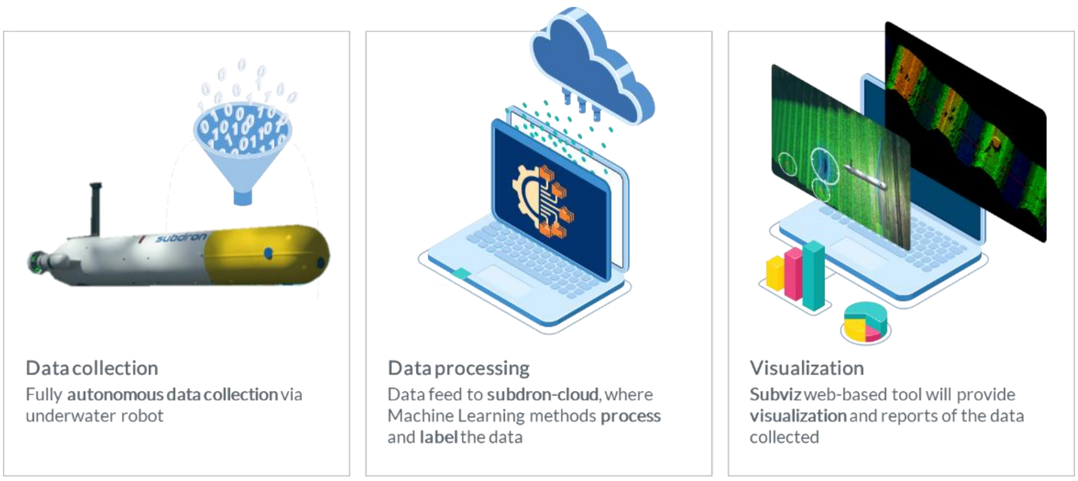

Fig.1: Main concept of Subdron solution

The following section will explain in more detail each of the main parts of the solution.

2. 1. Data collection

Subdron has developed a navigation and localization technology, which is the cornerstone of the end-to-end autonomous underwater inspection solution. The patented technology, called Relative Object Navigation (RON), combines hardware and software, allowing any AUV to safely navigate in a close environment.

The hardware contains two MRS (Mechanic Rotating Sonar) sensors. One is horizontally positioned, and the other one is vertically. Each of them scans the environment in its respective direction to automatically detect and differentiate the desired inspected structure from its surrounding environment. The distance between the vehicle and the object is continuously measured. Meanwhile, the Multibeam Echosounder (MBES) collects high-resolution 3D information on the inspected object. The main advantage of acoustic sensors is that they are highly robust and not affected by turbidity or low visibility. It also includes complementary sensors like a Sound Velocity Sensor (SVS) to adjust the acoustic sensors, an underwater communication modem to communicate continuously with the surface and a Global Navigation Satellite System (GNSS) antenna with Real Time Kinematic (RTK) capabilities to obtain highly precise positioning while on the surface.

Moreover, this solution is flexible and can be adapted to different use cases. For example, changing the location of some sensors or even replacing some of them, like MBES, could replace an optical sensor or stereo camera. Subdron is currently tackling two different use cases that require different configurations. p.dron is used for mapping underwater vertical infrastructures and needs the MBES pointing on the side, Fig.2, while v.dron is designed to detect biofouling and anomalies on vessels and requires the MBES to look on the top, Fig.3.

Fig.2: p.dron

Fig.3: v.dron

Subdron's navigation and localization software continuously processes the data gathered by the sensors. The information is processed to identify the surrounding objects (e.g., port walls or vessels' keel), allowing its relative localization. This removes the dependency on global localization systems during underwater scanning. With this information, the navigation software can follow the best trajectory to collect data on the inspected infrastructure, maintaining high precision in the localization and guaranteeing the full coverage of the infrastructure. The vehicle's position is adjusted using control commands at a medium-low level, which is available in most AUVs/ROVs.

Our software also allows scans collected by the sensors to be geo-referenced with a navigation accuracy of 10cm, and the accurate positioning guarantees that the totality of the infrastructure is covered using multiple scans. The data gathered is later used to reconstruct a complete 3D model or photomosaic of the object. Any underwater vehicle using Subdron technology will only require attention during the deployment and recovery. The customer can monitor it from the shore or a boat, decreasing the cost of regular inspection and surveillance. Furthermore, the unit has safety measures to abort the mission and go to a safety zone where it can be recovered safely.

2.2. Data Processing

Once the mission has finished, the data can be obtained via WIFI from the surface or by cable once the vehicle is on the surface. Then, the data will be transmitted to the Subdron's cloud infrastructure, where it will be processed. The cloud automatically tabulates and organizes the imaging data in 3D point clouds using a set of machine learning algorithms. This allows the system to create 3D reconstructions of the inspected structure with a cm accuracy level.

Different machine learning algorithms are trained to automatically identify and mark potential anomalies in the shape of deformations, cavities, foreign objects, and biofouling presence, including levels of thickness. These algorithms are also trained to identify changes in data collected from the inspection of the same object at various times. The acquired data, together with ship route data, can build predictive models and help understand biofouling behaviour and influencing factors. The added value of the cloud is reducing the time to process high quantities of data to reach conclusive inspection results. The areas of importance are already highlighted so the user can quickly navigate the data collected, thereby saving the user time and simplifying the task of the expert.

2.3. Visualization

All the data processed by the cloud is uploaded, processed, and displayed on a user-friendly web-based tool. The user can visualize, interact, and manipulate the collected data. Furthermore, this information is presented to the user in a highly usable and intuitive way without needing expert experience in underwater point cloud data. The user is also provided with various tools to explore the 3D reconstructions and track them over time. The added value of the tool is that it simplifies inspection reporting by giving users usable inspection results in a quick turnaround and fusing all the data in a single model. It also creates a breakthrough in the ability to perform predictive and targeted maintenance.

3. Biofouling in ship hulls and infrastructure

These days, biofouling is typically detected using visual sensors such as underwater cameras to spot the presence of biofouling. However, visual technology has its limitations when it comes to inspecting vessels. The main limitation is that this method can only be employed with sufficient water visibility. Additionally, visually identifying the type of biofouling does not allow for precise classification, such as understanding the exact thickness level.

Subdron is currently exploring the potential use of acoustic sensors to detect the presence and thickness of biofouling on vessel surfaces and infrastructure. By leveraging the capabilities of the Subdron solution for biofouling detection, a comprehensive map of the infrastructure surface can be created. This map will indicate the presence of biofouling and its thickness at each point, providing valuable information for the cleaning process. This approach offers several advantages. Firstly, it enables better preparation by identifying the necessary tools. Secondly, it optimizes cleaning time, as some areas require minimal or faster cleaning than others. Thirdly, regular inspections can help owners identify areas prone to biofouling buildup and implement better preventative measures. Lastly, the Subdron solution can be used post-cleaning to verify the effectiveness of the cleaning process.

In the previous section, we discussed the flexibility of our solution. We can incorporate a biofouling detection sensor into our current solutions (p.dron or v.dron), or we may need to develop a new solution. In either case, we will use the same navigation and localization software and hardware. We will integrate new algorithms for classification into the data processing module and visualize the data using the same web-based tool. This will allow us to combine 3D information with biofouling detection.

4. Results

Subdron has been testing the technology in several scenarios; at this moment, the development of the p.dron solution has reached a Technology Readiness Level (TRL) 8. Instead, the v.dron solution is still in a more early stage, reaching a level of TRL6. This paper presents one example of each product and the results obtained.

4.1. Inspection of a port wall

p.dron was demonstrated in the Port of Rotterdam, and the objective was to inspect a section of a port wall of 25 m length by 10 m depth. The harbour's wall combines three sheet piles for each circular pile. In the wall, there was also an outlet valve of 1.27 m diameter, a small valve of 0.28 m diameter, a horizontal square rail of 0.05 m, a vertical square rail of 0.06 m and the lock between sheet piles had a size of 0.05 m. In the inspected area, the wall didn't present any damage. p.dron solution was able to scan the wall section and generate a point cloud of the infrastructure. In the point cloud, it was possible to identify and measure all the distinctive elements of the wall. The measurements have an average error of 0.013 m, a standard deviation of 0.0074 and a coefficient of variation of 3.87 %. Fig.4 compares the 3D model of the port wall used during the port design and the point cloud collected.

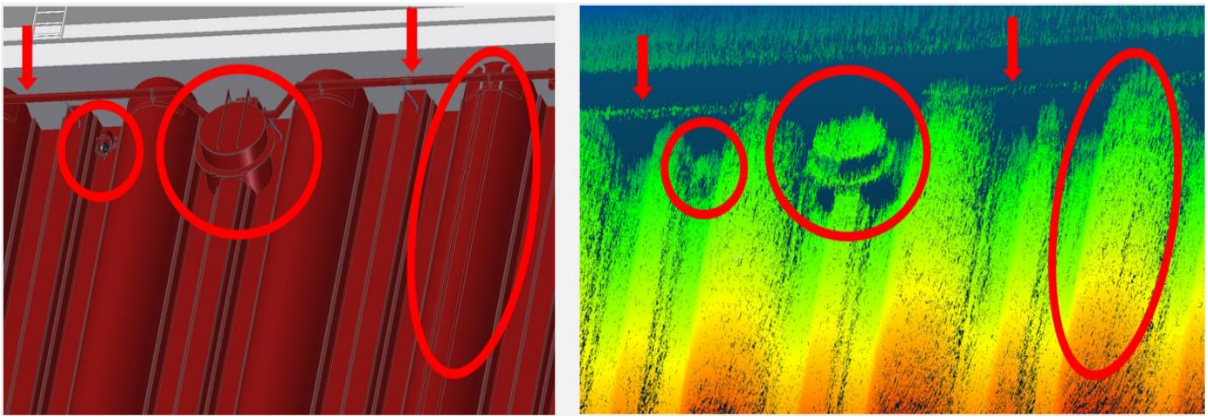

Fig.4: 3D model of the wall design (left) and point cloud obtained by p.dron (right). In both images, some elements are highlighted, from left to right: horizontal rail, small valve, outlet valve, and vertical rail.

Table I: displays the measurements of the several elements in the port wall and compares them with the measurements in the point cloud.

Table I: Measurement comparison of the point cloud collected and the design measurements

Name	Measure [m]	Mean of Point Cloud [m]	Error [m]	Std Deviation	Coefficient of Variation * [%]
Outlet Valve – Inner side	1.2700	1.2542	0.0158	0.01660	1.32656
Outlet Valve – Rim side	0.1330	0.1238	0.0092	0.00473	3.82085
Small Valve – width	0.2800	0.3081	0.0281	0.00140	0.45439
Sheet Pile Wall – Piles	0.4170	0.3903	0.0267	0.01150	2.94696
Sheet Pile Wall – Locks	0.0516	0.0529	0.0013	0.00114	2.16943
Sheet Pile Wall – Circular Pile	1.4200	1.3780	0.0420	0.01248	0.90574
Sheet Pile Wall – Vertical Rail	0.0600	0.0601	0.0001	0.00268	4.45984
Sheet Pile Wall – Horizontal Rail	0.0550	0.0553	0.0003	0.00870	15.7219

4.2. Inspection of a flat bottom

v.dron was demonstrated in the Port of Antwerp, and the objective was to cover the flat bottom of the Brabo barge, which has dimensions of 60m length by 30m width. The Brabo barge has two anchor chests on the stern and one anchor chest on the bow, a small keel and some drainage holes on the flat bottom. Unfortunately, in this case, we didn't have access to the ship's design information, so our measurements could not be compared with the ground truth. However, as seen in Fig.5, we were able to identify and measure one anchor chest, two drainage holes, the keel and the shape of the bow.

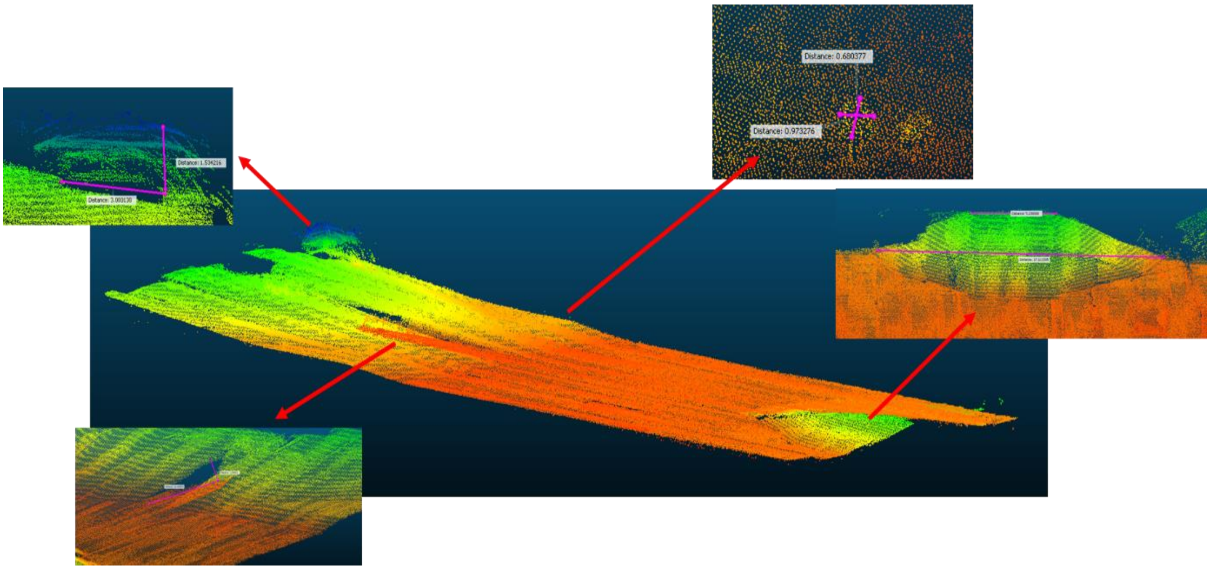

Fig.5: Point cloud reconstruction of Brabo barge with close-ups of the different elements identified

4.3. Preliminary results of biofouling detection using acoustic sensor

Until now, the technology has only been tested in a water tank using a single-beam acoustic sensor. The sensor took measurements of two metallic objects, one with biofouling on the surface and the other without it. Both objects were identical and had the same properties. The measurements showed that when biofouling was present, there was a decrease in the higher frequencies, as shown in Fig.6. This decrease in the signal suggests that analysing the amplitude obtained at different frequencies could be used to determine whether a surface has biofouling. These are preliminary findings in a controlled environment, and further research and development are necessary to understand the capabilities and how they will impact real-world measurements.

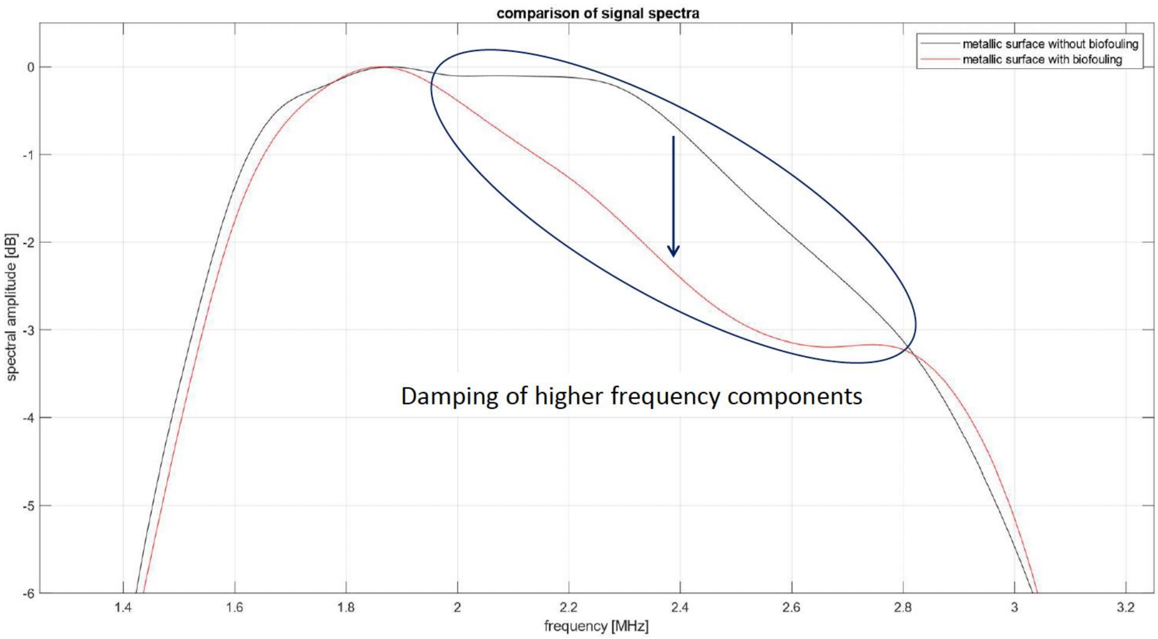

Fig.6: Signal spectra of a metallic surface with (red) and without (blue) biofouling

5. Conclusion

Subdron's end-to-end autonomous underwater inspection solution marks a significant advancement in underwater inspection for port assets and ship hulls. The ability to collect high-resolution data in low-visibility waters and navigate confined environments safely while performing 3D scans makes it a pioneering step forward.

This innovation will facilitate inspections in challenging conditions and ensure comprehensive monitoring by converting acoustic data into detailed 3D models. The subsequent data analysis provides critical insights into potential issues, enabling predictive maintenance. Furthermore, Subdron's ongoing development of acoustic sensor technology to detect and classify biofouling further improves the utility of our solution.

The paper features two demonstrations of port and ship inspection use cases, showcasing high-quality results that highlight the capability to perform accurate and reliable underwater inspections in challenging environments. Additionally, it includes preliminary results demonstrating the possibility of detecting biofouling using acoustic sensors.

The benefits of Subdron's technology extend to both Port Authorities and Ship Owners. For Port Authorities, the enhanced monitoring capabilities and the creation of digital twins of their infrastructure lead to improved asset management and operational efficiency. Ship Owners, on the other hand, gain precise assessments of hull conditions, which are crucial for maintaining vessel performance and reducing maintenance costs.

Overall, Subdron's services significantly elevate the quality and efficiency of underwater inspections. By reducing the time and cost associated with these processes, Subdron not only offers a cost-effective solution but also sets a new standard in underwater asset monitoring. The integration of advanced technologies in underwater inspection heralds a new era of maritime maintenance, ensuring safer and more efficient operations.

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The Clean Hull Initiative: Cooperation as Key to Establishing Proactive Management as a Universal Approach to Biofouling

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Abstract

The Clean Hull Initiative (CHI) is an international alliance initiated by the Bellona Foundation that consists of a broad range of stakeholders, including ship owners, ports, service providers, coating providers and researchers. Many of these stakeholders are competitors in the market, but they have chosen to join their forces in an alliance to work towards a common goal: To increase awareness of the benefits and importance of proactive biofouling management. Two years ago, these stakeholders formed the CHI. Under the leadership of the Bellona Foundation, the CHI co-authored a proposal for a new standard on in-water cleaning (IWC) to the International Organization for Standardization (ISO). Currently, a large group of experts consisting of many members of CHI have continued to successfully develop the ISO-standard on in-water cleaning. CHI aims to reduce barriers for the further uptake of environmentally sound proactive tools to prevent and minimise biofouling. Stakeholders involved in CHI see the benefits of coordinating their efforts, knowing that they should and will have a role to play in a future where proactive biofouling management has become the most common and universal approach to biofouling.

1. Introduction

Today, there is indeed a market for in-water cleaning (IWC), but in light of the tremendous size of global shipping, it is negligible compared to the total addressable market (also called TAM) for IWC. Considering the environmental benefits of IWC, it is important to achieve the full potential of that market, and stakeholders involved in IWC should set their competing interests aside and direct their attention towards the total addressable market of IWC. A market for IWC will not only rely on the availability of IWC service providers, but on the interest of ship owners to conduct IWC and the willingness of nations, ports and other relevant authorities to allow IWC in their waters.

Today, stakeholders such as IWC service providers and coating manufacturers are not only challenged by competitors in their own market, but they are also challenged by actors in other markets, for example those that compete for the same energy efficiency investments. Furthermore, these stakeholders are challenged by regulations that classify their products or services as unfavourable or restricted, and if future regulations increasingly restrict IWC, that may reduce the size of the current market for IWC.

Ultimately, the key to the total addressable market for IWC lies at the level of the International Maritime Organization (IMO). The main driver for the market of IWC does not yet exist, but will come into existence when the IMO develops regulations on the management of biofouling. However, in the wait for such international regulations, a range of other factors will influence the expansion of the market for IWC. Awareness raising will be essential for the total addressable market for IWC to form. Actors involved in the existing market for IWC should join forces to increase that awareness, and the Clean Hull Initiative (CHI) provides a platform for that.

2. The Clean Hull Initiative (CHI)

The CHI was launched in 2021. As of September 2024, the CHI has around 40 stakeholder members, and the group includes global ship owners, operators, regulators, port authorities, cleaning and biofouling removal technology developers/service providers, test facilities and the scientific/research community. The CHI aims to address the lack of comprehensive biofouling management policies worldwide, and aims to provide a level playing field for a range of stakeholders, thereby making a contribution towards harmonized regulations. Through the promotion of more consistent policies, the

CHI hopes to make it easier for the shipping industry to manage biofouling proactively, and to arrange for in-water cleaning service providers to smoothly operate in several locations. Working towards this goal, the Clean Hull Initiative initiated an ISO standard for IWC a few years ago, and the development of such a standard is ongoing and will be finalized during 2025, *Oftedahl and Skarbø (2021), Skarbø (2022), Tvedten (2023).*

3. Common terminology and common approaches

The advantages of IWC are obvious to service providers, researchers, coating manufacturers and others that work on this topic on a daily basis, but these advantages are poorly communicated to stakeholders such as ship owners and regulators. Ship owners arguably both underestimate the benefits of IWC and overestimate the risks that IWC pose to their coatings. Ports and relevant authorities tend to limit their interest in IWC to the risks it involves locally, and since many of them overlook how IWC can add to their sustainability strategies, they too often limit their approach to restricting IWC.

A first and important step towards the total addressable market for IWC, is to establish a common language and terminology for IWC. During the last few years, many of the stakeholder members in the CHI have been part of discussions about the meaning of various frequently used terms. For example, is proactive IWC about preventing macrofouling, as in the IMO's definition, or is proactive IWC about maintaining a ship in a clean state, minimising the establishment of microfouling? Is proactive IWC scheduled, or is such cleaning triggered by particular risk factors? Can you clean proactively with capture, or is proactive cleaning per definition without capture? Is proactive cleaning an individual cleaning of a ship, or is it a regime consisting of a chain of cleaning events? Depending on who you ask, people tend to have different answers to such questions. Through the collaborative arena of CHI, and in the context of developing the mentioned ISO standard, the CHI has come close to a consensus on what terms such as proactive IWC, reactive IWC and compatibility mean. Streamlining the use and understanding of terms will make it easier to routinise IWC as part of any green shipping activity, for example as part of Green Corridors.

A second step towards the total addressable market for IWC is to establish a consensus on environmentally sound procedures for IWC, which will help to harmonise regulatory approaches to IWC globally. The ISO standard that CHI has initiated is an example such an effort, and the IMO is currently developing an addition to its 2023 Biofouling Guidelines, *IMO (2023)* that also goes into the details of how to safely conduct IWC.

3. Conclusion

In a future where proactive biofouling management has become the most common and universal approach to biofouling and an established part of ship owners' energy efficiency strategies, a large market for IWC solutions will have emerged. The realisation of that specific future will rely on the whole IWC community to align their arguments and approaches to successfully communicate the benefits of IWC.

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Learnings and Challenges with Water Quality Testing Related to Proactive In-Water Cleaning

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Abstract

The shipping industry is under pressure to reduce its environmental impact and carbon footprint, while also facing the threat of invasive aquatic species that can harm biodiversity and ecosystems. One way to address these challenges is to use a biofouling management solution that combines a specially designed coating with a proactive in-water cleaning robot. This solution aims to keep the hulls of ships clean and thereby reducing drag, fuel consumption and emissions, as well as preventing the spread of invasive species. However, implementing this solution requires the involvement and approval of various stakeholders, such as regulatory bodies and port authorities, who need to ensure that the in-water cleaning operations do not pose any risk to the water quality or the marine environment. This paper will share learnings and challenges related to the performance, testing, and regulation of this innovative biofouling management solution – with special focus on a method for effective and accurate water quality testing.

1. Introduction

The need to improve sustainability in the shipping industry is accelerating. The global industry must cut carbon emissions and protect the marine biodiversity. Reducing the accumulation of biofouling on ships' hulls limits the spread of invasive aquatic species and reduces fuel consumption and thereby carbon emissions from shipping.

The most efficient way of controlling biofouling on ship hulls is the use of antifouling coatings containing biocides and, in most cases, an antifouling coating is sufficient to keep the ship clean. In cases where the fouling protection fails due to especially challenging trade, changing operational profile or deviation in fouling pressure compared to what was expected during coating specification, cleaning of the hull might be necessary to remove biofouling to reduce fuel consumption and greenhouse gas emissions as well as limiting the spread of invasive aquatic species. Cleaning has traditionally been performed only when a ship has collected a significant amount of fouling with the corresponding reduced performance, increased fuel consumption, green gas emissions and danger of transporting invasive species with potential negative impact on the marine ecosystem. With the increased focus on sustainability, reduced fuel consumption, emissions, cost and protecting the marine environment, ship and environmental data is more extensively being collected and used to monitor ship performance. The focus is shifting towards a more proactive approach which includes cleaning of ships at an earlier stage to reduce negative impact of marine fouling. This proactive cleaning has been increasingly advocated, e.g. by *Hunsucker et al. (2018)*, *Swain et al. (2020)*. Jotun has also been active in promoting a corresponding standard for in-water cleaning, *Oftedahl and Skarbø (2021), Oftedahl et al. (2022), Skarbø (2022)*.

2. Challenges

Several international and local regulatory bodies are working on development of guidelines, standards and policies related to in-water cleaning of ship hulls.

The International Maritime Organization's (IMO) *Guidelines for the control and management of ships' biofouling to minimize the transfer of invasive aquatic species* (2023 IMO Biofouling Guidelines) was published as a final draft in April 2023 and adopted by MEPC 80 in July 2023. A separate guidance related to in-water cleaning is to be developed with the target of completion in 2025, *Tvedten (2023).*

The International Organization for Standardization (ISO) has also established a working group that is developing an international and industry-wide recognized standard on hull cleaning with the objective to provide a best practice methodology to assist and facilitate the implementation of environmentally responsible hull cleaning procedures and methods for documentation of the operations. In addition, the working group is developing Guidelines for testing ship biofouling in-water cleaning systems with the objective to provide detailed and rigorous procedures for the impartial performance testing for all forms of in-water cleaning of all types of biofouling. The aim is publication by January 2026.

National initiatives are also either already active or being developed, making the picture even more complex. New Zealand has been in the forefront with their Craft Risk Management Standard: Biofouling on Vessels Arriving to New Zealand 2018, setting standards for the underwater hull fouling condition upon arrival to New Zealand, and documentation of this. In Australia the Department of Agriculture, Fisheries and Forestry has developed Antifouling and in-water cleaning guidelines with detailed requirements for and documentation of a ship's hull condition.

In Europe, the Flemish ports; Port of Antwerp, Port of Zeebrugge and North SeaPort (Port of Gent) have also developed detailed procedures for hull cleaning, testing and approvals.

The current inconsistencies in policies and the plurality in initiatives is challenging not only for the shipping industry developing a biofouling management but also for any in-water cleaning service providers trying to manage operating in several locations (GloFouling 2022). Jurisdictions that do not have any system, either allow cleaning without any criteria or do not allow cleaning because they have no regulations to lean on.

In addition to ongoing regulatory initiatives, a general knowledge gap in many disciplines is another challenge working with the clean hull approach. The overall capabilities of various cleaning technologies regarding risk to the environment at the cleaning site is not known. Knowledge building is required both for service providers, port authorities and other entities regulating underwater cleaning. The industry is dependent on the allowance for operation while the technology is continuously improving to impose less and less negative impact on the environment.

We also experience that background levels and seasonal variations in ports are often unknown, not available or not sufficiently mapped. Mapping of background levels and knowledge of seasonal and geographic variations are important when port authorities are evaluating permits for cleaning based on water quality testing of in-water cleaning technologies.

When adopting proactive cleaning as part of our solution to keep ship hulls clean it is necessary to gather knowledge on capabilities and performance both for internal learning, technology development as well as data on environmental impact for port authorities to get approvals for operation. Detailed and rigorous test schemes have been developed, as the Guidelines for testing ship biofouling in-water cleaning systems developed by The Alliance for Coastal Technologies (ACT) and Maritime Environmental Resource Center (MERC), led by Dr. Mario Tamburri, in collaboration with the US Naval Research Laboratory (NRL), Smithsonian Environmental Research Center (SERC), and California State Lands Commission (CSLC). Other similar ones are also under development, e.g. the mentioned ISO Guidelines for testing ship biofouling in-water cleaning systems or local test regimes.

The test schemes are very comprehensive, labour and time consuming, which is often not matching to what is possible to achieve in practice during a port call of a ship. There are often prioritised activities like bunkering, cargo operations, shortening of port stay and shifting between berths in port that make the time planning difficult and test time slots unpredictable. Consequently, the testing must be as efficient as possible. There has been a need to simplify as a starting point, learn and evolve on the way and broaden the scope when it is seen fit and possible.

3. Jotuns ambition

Since 1926 Jotun has been on a mission to protect property in every corner of the world. It began with a solution to protect ice going ships travelling to the Southern Ocean from corrosion. Today Jotun protects assets in a wide variety of industries and is a global market leader in marine coatings and hull performance solutions. Jotun's aim is to protect the environment and create value by contributing to customers' sustainability ambitions and goals. Jotun is committed to continuously innovate and develop advanced products and solutions designed to protect biodiversity and cut carbon emissions to support global sustainability ambitions and achieve cleaner operations for all industry players. Jotun has a range of services, products and digital capabilities solving customer challenges today. The Jotun Clean Shipping Commitment (www.jotun.com/no-en/industries/shipping) emphasize the impact of a clean hull to reduce speed loss, ship down time, protect biodiversity, reduces fuel consumption and carbon emissions.

3.1 Jotun Hull Skating Solution

Jotun has adopted proactive cleaning as part of the Jotun Hull Skating Solutions (Hull Skating Solutions | Jotun | [NO]). The Jotun Hull Skating Solution is designed for operations where ships performance is lowered due to fouling and cleaning is required to keep a ship's performance, control biofouling and reduce the potential for release of invasive species. A primary component of Jotun Hull Skating Solutions is the unique, onboard HullSkater, the first robotic technology that has been purpose-designed for proactive cleaning. The solution includes a proactive ship in-water cleaning system designed to reduce growth on submerged ship surfaces and keep ships clean, as part of a ships biofouling management program. In combination with the premium SeaQuantum Skate antifouling coating and a set of services, Jotun Hull Skating Solutions will help ship operators combat early-stage fouling, significantly reduce fuel costs, greenhouse gas emissions and hinder the spread of invasive species.

3.2 SeaQuantum Skate

SeaQuantum Skate has been developed specifically to optimise performance in combination with Jotun HullSkater. The coating is designed to endure repeated mechanical contact with the proactive cleaning unit on the HullSkater without eroding or damaging the coating. SeaQuantum Skate is a chemically hydrolysing silyl methacrylate so called self-polishing antifouling coating. The antifouling performance is achieved by hydrolysis and polishing of the coating with the subsequent continuous and slow release of biocide compounds for fouling prevention.

The coating contains copper oxide and copper pyrithione as biocides, and they release Cu^+ ions upon contact with seawater that diffuse to the coating surface and the seawater. In addition, the coating contains zinc oxide and iron oxide that also will be released into the seawater. Zinc oxide is the most water soluble of the three whereas iron oxide is considered less soluble. After hydrolysis and release of biocides, an outer insoluble porous layer called leached layer, typically 20-30µm thick will form. The leached layer consists of coating compounds with lower water solubility.

3.3 Compatibility between SeaQuantum Skate and the HullSkater

The solution design enables proactive and gentle cleaning of the antifouling coating without negatively affecting the physical integrity or function of the coating. Extensive testing during cleaning operations has been performed on ships in global trade with both new and aged coatings with the focus on mechanical impact on the coating. This has also been supported by lab tests and tests on static structures in the sea.

The testing has shown that no erosion is detected, no degradation of the coating film and no erosion or reduction in thickness of the leached layer.

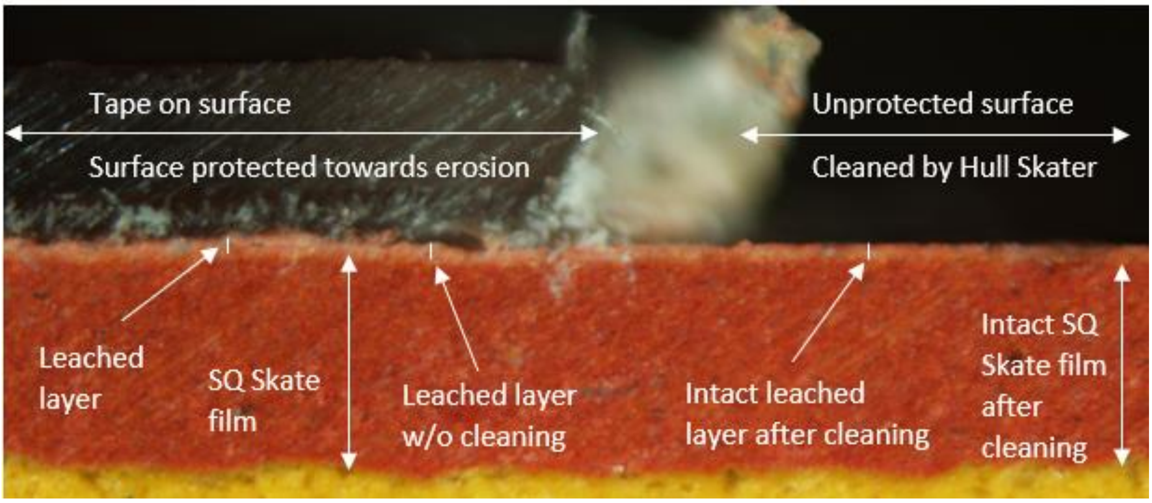

Fig. 1: Microscope image of SeaQuantum Skate paint after repeated cleaning passes of Hull Skater over the surface showing intact leached layer of 15 µm on top of intact antifouling coating of 200 µm

4. Biocide leaching and proactive cleaning

A self-polishing antifouling coating with copper oxide and copper pyrithione as biocides will during ship sailing and port calls without cleaning continuously release biocides to prevent fouling growth on the surface. This release is relatively predictable throughout the lifetime of the coating. Copper is an essential element in nature and occurs both naturally and anthropogenic and there is no difference in the two forms. In general, the major input of copper into the oceans are copper eroded or dissolved from bedrocks and riverbeds and supplied by rivers. Still, the environmental impact of anthropogenic copper is important to focus on. The biocide release from antifouling coatings is highly regulated and calculation models are used to ensure that the release does not impose an unwanted negative environmental impact.

The impact from the HullSkater on SeaQuantum Skate has been thoroughly tested both in test facilities in laboratory conditions, on static structures and on ships in commercial operation. No degradation or erosion of the SeaQuantum Skate antifouling has been detected during operation of the HullSkater. With no degradation of the coating, the components released during proactive cleaning will mainly be components washed out from the porous outer leached layer and components associated with the surface and with the microfouling (slime layer) on the surface. Fig.2 illustrates the theoretical release of e.g. copper from the coating during a proactive cleaning regime.

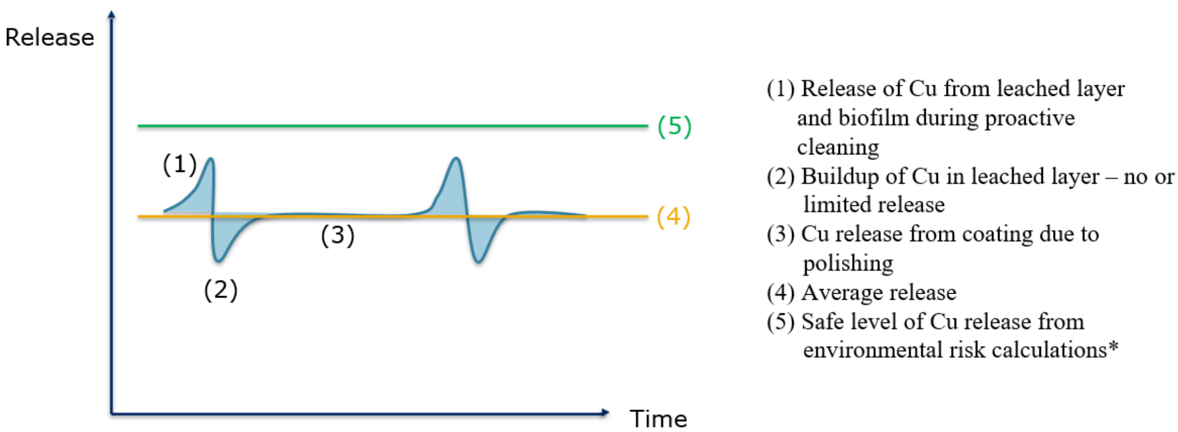

Fig.2: Theoretical release of copper from antifouling coating during a proactive cleaning regime. *Note: PEC/PNEC<1 for the relevant product, vessel and harbour scenario

When a cleaning is performed, copper ions from the leached layer will be washed out and released. After the release, the concentration of copper ions in the leached layer is lowered and the leached layer is considered empty. The dissolution of copper will continue in the coating and copper ions will diffuse out filling up the leached layer. The equilibrium of copper ions between the leached layer and the water phase is re-established with a continuous copper release as the coating polishes. Then the scheme will repeat itself until the next cleaning. The average leaching rate over time will not be disturbed by the cleaning operation.

5. Water quality testing

The water quality testing has been performed on a selection of vessels to get a spread in trade and lifetime of the coating. The test scheme has been a simplification of the ACT/MERC test procedure.

The simplifications were made to enable testing within the given timeframe and resources available. The assessment of the expected hull condition with regards to fouling was done by performing inspection in a port close in time prior to the testing or using reports from previous inspections. In-situ inspection of fouling on the hull was done during the cleaning operation, live video for in situ evaluation and captured video and photo material for report purposes. The areas to be cleaned was limited to paths to enable time efficient testing within the time available during a ships port stay and in between activities such as bunkering or shifting between berths in port. The cleaning efficiency was recorded in situ with live video and video and photo material was stored for documentation.

The water samples were taken on a sampling point on the HullSkater while cleaning paths of the underwater hull. Reference samples were taken on the HullSkater at test depth, at three points in the water line alongside the ship as well as from the water line at key side in the harbour. Samples were collected from the sampling point on the HullSkater via a 50 m hose connected to a sampling pump positioned onboard a support vessel alongside the test ship as illustrated in Fig.3. Samples were collected in sample bottles for transport to and analysis at an external laboratory.

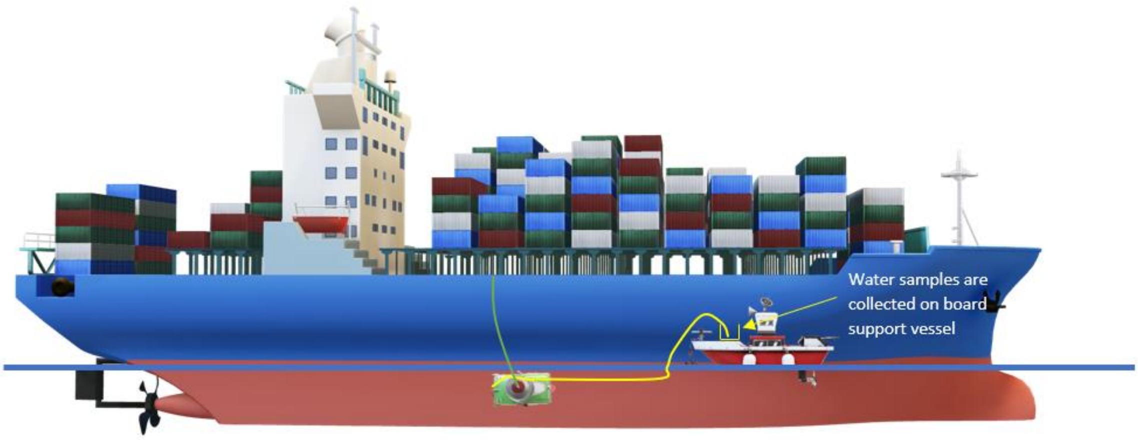

Fig.3: Collection of water samples via hoses connected to the HullSkater

The water quality testing was typically performed along several cleaning paths as shown in Fig.4. Each path was approximately 30 m long. Reference samples on the HullSkater were typically taken on the starting point of Path 1. Reference samples alongside the ship before and after testing was taken in the waterline in position A, B and C.

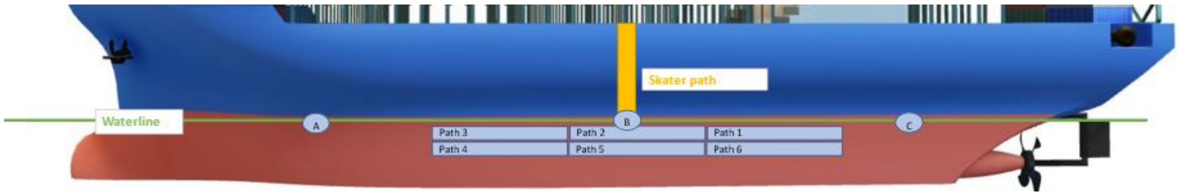

Fig.4: Cleaning paths and reference sample points alongside for water quality testing

The focus of the water quality testing has up until now mainly been measuring the release of total copper, iron and zinc during the proactive cleaning of SeaQuantum Skate with the HullSkater. Copper and zinc ions will be present in the water phase inside the leached layer and associated with the surface. Iron is included in the analytical scheme as it has lower water solubility and will be present in the insoluble leached layer. An increased level of iron would then indicate degradation of the leached layer.

6. Environmental risk assessment

The environmental risk of release of biocides from antifouling coatings is strongly regulated to protect especially local areas and harbours. When conducting risk assessment of antifouling coatings, it is necessary to determine the release of the biocides and substances of concern, like copper and zinc from copper oxide, copper pyrithione and zinc oxide. Under the EU Biocidal Products Regulation, it is of particular importance to measure the release rate from vessels laying idle in ports and harbours.

Release rates from the testing has shown low values of e.g. copper and zinc in the collected water samples. One must always strive to have as little as possible impact on the surrounding environment but zero impact is not possible. Both samples from testing and especially background samples have shown a relatively large variation in measured values. Based on this, the focus needs to be on the possible environmental risk of cleaning, and the same considerations and risk assessment used for antifouling coatings must apply for cleaning of ships coated with antifouling coatings.

To calculate the risk of having ships coated with a biocidal antifouling coating visiting a port, a MAM-PEC computer model is used. This is the governing tool used by the competent authorities in EU member states. The model is based on Rotterdam harbour, thus representing a worst-case scenario due to the high number of large ships per area in the harbour, its position along a large estuarine river, and very low water exchange.

The environmental risk associated with proactive cleaning with Jotun HullSkater on SeaQuantum Skate was calculated using the MAM-PEC model. Based on the measured released copper (from cuprous oxide and from copper pyrithione) and zinc (from zinc oxide), the model calculates the predicted environmental concentration (PEC) of each substance in the water and the sediment. The PEC is then compared to the predicted no effect concentration (PNEC), i.e. the PEC/PNEC ratio is calculated. If this ratio is < 1, it means that the predicted concentration is less than the harmful concentration. A pragmatic and conservative approach to estimate the combined risk from several substances is to add the ratios, i.e. PEC/PNEC of cuprous oxide + PEC/PNEC of copper pyrithione + PEC/PNEC of zinc.

Calculations done for the measured values during HullSkater cleaning on SeaQuantum Skate gave a sum $\sum$PEC/PNEC < 1, both in the water and in the sediment, i.e. the release levels detected does not impose any environmental risk.

7. Conclusion

Jotun has adopted proactive cleaning as part of the Jotun Hull Skating Solutions with the commitment to keep ship hulls clean to reduce fuel costs, greenhouse gas emissions and hinder the spread of invasive species. Testing on vessels in operation coated with SeaQuantum Skate antifouling has proven that the presented simplified method is suited for learning and performance evaluation and for gathering data required for port approvals. Testing has also proven that proactive cleaning without capture can be done without imposing negative environmental impact as calculated by the EU governing MAMPEC tool.

Acknowledgement

Performing water quality testing during operation of the Hull Skating Solutions would not have been possible without world-class partners, which we gratefully acknowledge. Thanks also go to the many colleagues at Kongsberg, Wallenius Wilhelmsen and our other customer partners.

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From Regulator to Regulated: A Perspective from Both Sides

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Abstract

This paper discusses the current challenges surrounding effective regulation of in-water cleaning of ship hulls, a current scenario where biofouling management is required but solution access is restricted, and a possible pathway to fit-for-purpose regulations for a vital activity drawing on the author's own experience as a former regulator and now service provider. Biofouling on vessel hulls brings the risks of invasive species spread, unnecessarily expended greenhouse gases, and pollution. In-water hull cleaning is an activity that is necessary for good biofouling management but comes with the risk of invasive species spread and pollution when done without effective capture. Fit-for-purpose regulations are those which set a high benchmark to protect the environment and human safety, while also providing a clear pathway to reach that benchmark to allow for the needed innovation in the in-water cleaning industry to meet the shipping industry needs without putting the environment and human safety at risk.

1. Introduction

Global regulations on environmental impacts are locked in a race against the clock to pull climate change and the degradation of nature out of a nosedive. The frequency of the appearance of such regulations is ever increasing to try to outstrip the rate of further loss of a stable climate and viable global biodiversity.

In recent years, the active inclusion of biodiversity, not just climate, in the regulatory space has seen the eyes of policy and regulation turn more toward the key drivers of biodiversity loss, other than climate. In order of impact, the five key drivers of biodiversity loss are changes in land and sea use, direct exploitation of organisms, climate change, pollution, and invasive species.

Biofouling is the growth and establishment of marine organisms on submerged surfaces. This problem has plagued humans since the invention of boats. The biofouling issue links with three out of five of the five drivers of biodiversity loss, namely climate change, pollution, and invasive species. Thus, it is unsurprising that the topic of biofouling has come to the forefront of conversations around issues urgently requiring improved management in the shipping world.

New Zealand holds the title of being the first country to plant their flag in the sand on where they stand on biofouling on international vessels at a national scale. The Craft Risk Management Standard for Biofouling (CRMS) was released in 2014 and became actively enforced from 2018. New Zealand's requirements allow for the government to have a harsh and immediate response to unacceptable levels of biofouling, if required. The State of California also issued biofouling regulations for vessels arriving to California requiring vessels to carry evidence of on-going biofouling management. Both sets of requirements were designed to ensure international vessels managed biofouling to pose as low as possible biosecurity risk local marine ecosystems.

The New Zealand Ministry for Primary Industries (MPI) became responsible for finding a way to actively regulate something that was new to the shipping world. They needed to manage biofouling not just to lower the fuel bill, but to halt invasive species. The seriousness of this stance was not fully understood until the first vessels were directed out of New Zealand territorial waters (NZTW) due to their heavy biofouling posing a high biosecurity risk to New Zealand's biodiversity. This event not only hit international headlines, but it jumpstarted the biofouling conversation across the shipping world. Those in charge of overseeing and assisting with enforcement of the CRMS have a globally unique perspective on the challenges of the shipping industry.

While regulators begin to manage biofouling as a risk arriving on vessels to their shores, there is also a moving trend of regulators in ports closing their doors to the in-water hull cleaning services that are needed to remove biofouling. Vessel owners are feeling increasing pressure to manage biofouling to a higher standard than ever before, while also seeing a reduction in options to achieve that standard. This is in-turn working against the goal of reducing the negative impacts associated with biofouling.

Available literature and data on biofouling are improving, but there is still a vast knowledge gap on our collective understanding of the problem and its wider impacts on nature. This knowledge gap feeds frustration and mistrust between vessel operators, service providers, and regulators which often leaves the industry at an impasse. In turn, this has the potential to hinder development of fit-for-purpose regulations being developed that drive improved management of biofouling and allow for needed innovation in the industry.

2. The regulatory overview

The current landscape of regulations relating to biofouling management and in-water cleaning is spread across a broad scale ranging from minimal or no requirements to very strict. Most ports allow vessels to come and go without requiring evidence of on-going management of their biofouling, yet when removal in the form of in-water cleaning comes into the picture there is often a low level of tolerance, particularly in developed states.

It is generally accepted that biofouling should be continually managed through continual maintenance techniques to as low as possible levels to reduce invasive species risks and reduce fuel overconsumption. This is in line with *IMO (2023)*. However, it is less agreed upon on how and where in-water cleaning can be done, which is an essential and often inevitable part of biofouling management.

The lack of consistent facilitation of access to biofouling management solutions puts the shipping industry in a difficult position. They typically must decide on whether to not conduct a clean of their vessel and see the associated negative impacts worsen or clean their vessel in a port with low regulations and therefore untrustworthy solutions that can damage a major investment to protect their asset, the antifouling coating and put the local ecosystem at risk.

The current situation creates a stalemate where the biofouling problem is expected to be managed, but no one can agree on how to safely facilitate a key part of the management process. This disconnect between the problem and solution must be addressed before the shipping community can hope for global improvement of biofouling management and reduction of its negative impacts.

2.1. Biosecurity versus pollution

The lack of compulsory requirements for vessels to provide evidence of their management of biofouling, compared to the usual presence of restrictions in relation to in-water cleaning is likely due to the pre-existing legislative structure, or lack thereof, a country has in relation to the two issues. Biosecurity specific legislation is not typically strong enough to allow management of a complex pathway such as biofouling arriving on international vessels, whereas pollution related legislation is universally present and well established and understood.

Countries such as New Zealand and Australia are geographically isolated countries that can leverage that isolation to keep pests and disease off their shores, largely to their economic and social advantage. Therefore, they have invested heavily in powerful biosecurity-specific legislation and enforcement systems which are modern, adaptable, and fit-for-purpose. This legislation is the appropriate tool to allow for active management of a complex biosecurity pathway such as international vessel hulls. Unfortunately, this level of biosecurity legislation and enforcement systems are not common across much of the world.

Due to the release of man-made pollutants (antifouling coating debris containing heavy metals and plastics) associated with traditional in-water cleaning, ports are typically able to apply regulatory structures for pollution management, like "land to sea discharge" rules, to manage the activity. In-water cleaning is more easily defined due to known substances likely to be discharged in high quantities and, therefore, has an enforceable structure supporting the ports in taking actions to manage the risks from this angle. However, these regulations were usually created with different industries and activities in mind and must be bent to fit the in-water cleaning activity, or rather in-water cleaning must bend to fit the regulations.

Another issue in existing rules is the double standard of how pollution is perceived in the ocean versus on land. Following capture on land from an in-water cleaning system, the cleaning debris is considered commercial toxic or contaminated waste and has strict rules regarding its handling and disposal. Additionally, often providers with capture systems will have their effluent water following filtration and treatment scrutinized by authorities because it falls into "land to sea discharge" categories where regulations typically exist. In the same port, just meters away could be an in-water cleaning provider using a partial or fully non-capture system releasing the same substances into the ocean with no additional cost or repercussions.

The overarching issue with this difference in the legislation used to manage the risks associated with in-water cleaning (pollution and invasive species) is that it often results in non-fit-for-purpose requirements or regulations being enforced to manage the risks. These requirements are often; difficult for in-water cleaning providers to adhere to due to over complexity or because they were designed for an entirely separate industry, not setting a high enough bar for environmental and human health protection because of their non-specific design, completely shutting the door to the activity leaving no room for much needed innovation.

2.2. The fit-for-purpose "sweet spot"

International ports can be placed on a spectrum, Fig.1, with two scales relating to where they stand with in-water cleaning management. One is a scale of strictness of regulations or requirements, and the other is a scale of the complexity of the application or permitting process. Both can be barriers to innovation in the in-water cleaning space for separate reasons. Depending on where a port sits on the spectrum can indicate whether their processes or regulations can be considered fit-for-purpose.

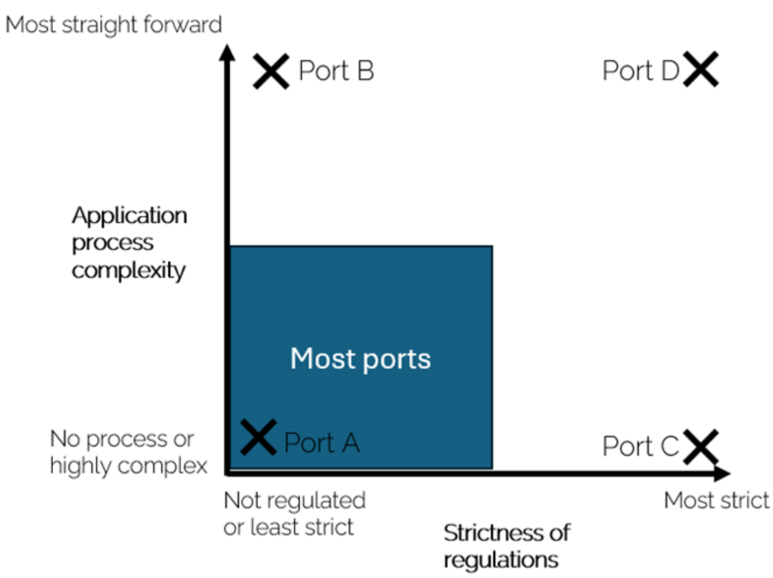

Fig.1: Spectrum of port in-water cleaning regulation, with example placements (port A, B, C, and D) of where ports can sit on the scale, and the area where many ports are likely to fall

In Fig.1, “strictness of regulations” (x axis) relates to the level of environmental protection and human safety, with low strictness equating to poor environmental protection and human safety, and high strictness equating to a strong level of environmental protection and human safety. The “complexity of the application process” (y axis) reflects the accessibility level for in-water cleaning solution providers to become established in a port through proving adherence to the requirements.

On the scale of “application process complexity”, the lower end is a port with either no permitting process or a highly complex one. These processes are usually not purposely complex by design, but they can be due to a lack of direction or structure to manage this type of activity. The impact of ports sitting at this end of the scale is that no or very few providers can gain access due to this complexity, or unfair selection of providers may occur due to inconsistency and lack of structure. Both pose a problem when considering the need for innovation and growth in the in-water cleaning space to overcome the environmental and human safety issues still prevalent amongst the industry. The shipping industry is also likely to find lower quality service providers, or ineffective supply at such ports.

At the upper end of the “application process complexity” scale is the most straight forward process. Ports that land on this end of the scale stand to see service providers gaining access due to a clarity of how to prove adherence to requirements. They are likely to host higher quality services from a vessel owner perspective due to more interaction and vetting, however, they are still vulnerable depending on where they land in terms of “strictness of regulations”.

On the lower end of the scale of “strictness of regulations” are ports that either have no regulations or existing regulations that set the bar very low. Ports landing at this end of the spectrum are at the highest risks from pollution and invasive species introduction due to partially open- or fully open-loop in-water cleaning likely being able to operate. These ports are not likely to drive innovation in the industry with regards to improvements of environmental impacts, human safety and quality of service. Being required to reduce environmental impact and human safety risks results in equipment design aimed at lowering unnecessary creation of debris (preserving antifouling coating), helping maintain control and capture of debris, and better verification of quality of work which in-turn benefits vessel operators. Low regulatory bars set by ports will not drive this type of innovation.

At the higher end of the scale of “strictness of regulations” are ports with the strictest requirements or regulations. Ports that sit on this end of the scale are at the lowest risk of negative environmental and human safety impacts from in-water cleaning due to setting a very high bar for providers. However, depending on where they sit on the “application process complexity”, they may not be likely to drive the needed innovation and development needed for technology to reach the pinnacle of environmental and safety performance.

“Port A” sits at the lowest end of both spectrums and is therefore unlikely to see protection of the environmental or human safety, nor a drive for innovation amongst the service providers it may host. It is also likely to host low quality services from a vessel operator perspective.

“Port B” is an example of the port eager to host the activity to ensure access for industry but does not prioritise environmental protection or human safety with low strictness of requirements. This type of port is unlikely to foster innovation due to a low regulatory bar and may host low quality service providers and inadvertently hinder industry rather than enabling it.

“Port C” is a port that has a strong stance on the activity with a high level of strictness but has no process or a very complex one for gaining access to the port as a service provider. This type of port is likely to be one that has entirely banned the activity and has no clear pathway for gaining approval through overcoming the environmental and human safety risks which caused them to ban it in the first place. While their high bar may drive in-water cleaning providers to try to innovate, this innovation is unlikely to occur due to a lack of transparency of what is needed to achieve reach the high regulatory bar.

Finally, “port D” sits on the strictest level of requirements, as well as the most straight forward and clear application process. What this would look like is a port that has prioritised environmental and human safety aspects but also has a clear view on what a provider must do to adhere to those requirements and gain approval. By setting a high regulatory bar with a visible pathway to reach that bar, the lack of ambiguity is likely to enable in-water cleaning providers in the process of innovation while also ensuring high quality services for the shipping industry. Ports in this category would be considered to have the most fit-for-purpose regulations that benefit all parties involved.

If ports can establish a level of regulatory requirements that appropriately manage the environmental and human safety risks associated with in-water cleaning, as well as lay out a clear approval process to show adherence to those requirements, the shipping industry is likely to see high quality, environmentally friendly and safe services more widely available. This would in-turn move industry closer to effective management of the biofouling issue, and therefore reduction in carbon emission, invasive species spread, and pollution.

3. Rules without solutions: the impacts

Both Australia and New Zealand require vessels to have clean hulls when operating in their territorial waters, but also do not currently allow in-water cleaning within their territorial waters on international vessels unless they have received full biosecurity clearance (i.e. cleared for permanent stay).

This stance makes sense considering the most common practice for in-water cleaning makes no attempt to capture debris and protect the local environment. To allow the activity would work against what they are trying to do by requiring ships to arrive with clean hulls.

However, the result of requiring clean hulls while not enabling access to solutions forces the shipping industry to use unsafe and low-quality solutions in ports elsewhere with little or no regulation with a high cost to the environment and their wallets. This is creating an attitude of “reluctant compliance” as vessel operators don’t see a short-term benefit from meeting these regulations because their potential gains are often lost due to bad cleaning jobs on their hulls. This situation also does nothing to help drive innovation and creation of solutions that protect the environment and human safety at risk in their own regions.

A major issue that is limiting solution providers being able to establish in their ports lies partly in there being no universally accepted method for testing in-water cleaning technologies accurately that covers both biosecurity and pollutant risks. Additionally, these solution provider companies are often unwilling to give the high level of access needed by authorities to understand their systems and risk management capabilities.

Overall, these countries having requirements in place does work to drive the global effort to manage biofouling, as they are creating consequences and forcing shipping operators to act and explore better biofouling management options. It can be argued that the global momentum on the issue would not be where it is without New Zealand starting their tough enforcement policy. However, they can be seen as a warning for what may happen if the current trend of increasing clean hull requirements and banning, or high restriction of in-water cleaning continues globally.

4. A road to fit-for-purpose regulations

A fit-for-purpose regulation is one that not only achieves the protection of whatever may be put at risk by an industry or activity, but also allows for those being regulated to meet the needs of community and industry while achieving that standard they set. While it is common for a regulatory bar to be set when industry may not be necessarily ready to meet that standard, they may be set up for failure if those regulations do not factor in room for innovation of solutions that help to reach that bar if they do not already exist or are not widely available.

The current reality with in-water cleaning is that solutions capable of proper environmental and human safety protection are not common. This is due to a lack of pressure to improve solutions in the absence of regulation. Additionally, the scientific community, regulators, and industry cannot agree on what "proper environmental protection" looks like, and how to test that solutions would meet that bar once it is set. The needed leap in solutions to fill the gap cannot happen without a presence of fit-for-purpose regulations that drive innovation but do not inadvertently stifle it.

Regulators typically have a high level of mistrust for in-water cleaning providers due to the historic lack of regulations. Vessel operators also have a low level of trust of service providers because they can often provide low-quality services that damage an expensive and important asset, their antifouling coating. This causes them to shy away from future investment in these solutions which in turn slows down progress towards good solutions that are widely available.

The pathway toward regulations that are needed to help solve the greater biofouling issue is one that requires a certain level of trust and openness from regulators, in-water cleaning providers, and vessel operators.

4.1. The mind of a regulator

Regulators have a complex job in any field of focus. They cannot know everything about the industry or activity they are regulating, nor can they be everywhere all at once. Therefore, they depend heavily on the stakeholders in the industry they regulate, be they members of the public, commercial business operators, the scientific community, or other regulators. These groups supplement what may not be available in literature or data sets. The relationship they have with these groups, and the quality of information they are provided with, is hugely influential to the final product, the regulations.

Due to regulators being unable to know everything and be everywhere, they depend on their stakeholders to help them understand the reality of the issues surrounding a field of focus to be able to supplement their understanding. A regulator must take perspective from scientific communities, industry, public, other regulators, data and literature and find a place to draw the line that everyone can agree is correct from where they stand. Of course, this is an impossible job. However, if a regulator is fed bad information, or pays more attention to one group over others, the result will be a regulation that is not fit-for-purpose. This can result in regulations that either don't serve the environment, the public, or industry, if not all three.

In the area of in-water cleaning, regulators must consider many aspects, to name a few; human health and safety, pollution risks, CO^2 emissions, biodiversity, marine invasive species, trade impacts, technological capabilities (current and possible future trends), port access, other regulatory restrictions, local legislation, national legislation, legal obligations to the public and industry, industry needs, local communities, and future generations. Dishonesty, misinformation, or misunderstanding coming from stakeholders they engage only destabilises the complex tightrope they walk to get to a regulation.

From the perspective of industry (vessel owners and operators, in-water cleaning service providers, and port operators), fit-for-purpose regulations relating to in-water cleaning are important for their daily operations and future. Without rapid development of more capable in-water cleaning solutions that remove human safety risks, protect the environment, and allow biofouling to be managed to stop unnecessary CO^2 emissions and invasive species spread, they stand to lose. It is in every group's best interest to ensure that regulators are given open access to their perspectives and operational reality in relation to in-water cleaning to foster development of fit-for-purpose regulations.

4.2. Filling an ocean sized data-gap

Despite biofouling being a long-standing issue in the shipping world, there is still a large data gap in our collective understanding. Biological problems are notoriously difficult to understand and manage due to the nature of nature, it adapts. Studies are often limited to locally or regionally operating vessels

or have a small sample pool comparative to the world fleet. There is much to be learned about the operational reality of biofouling on a global scale, and how impacts such as climate change are influencing biofouling communities.
In relation to in-water cleaning, this data gap is even wider, and herein lies another cause of reluctance in regulators to address in-water cleaning with robust regulations. It is incredibly difficult to set a bar with little understanding of where to focus risk management due to low information about the threats. Literature and data, as mentioned above, are a key part of building regulations. Just as bad advice from stakeholders can lead regulators astray, data gaps have the same potential.

An opportunity lies with in-water cleaning with full capture technology to lend volumes of data to supplement our collective understanding of in-water cleaning impacts and biofouling itself. When a system has full capture, the provider has control of what, in typical circumstances, a non-capture cleaning system would dump into the port waters. This debris holds information about the composition of the waste, for example the volumes of biological matter versus antifouling contaminants, or the types of species present.

Data as simple as the total weight of debris collected during cleaning can not only be valuable to ship owners in relation to measuring and predicting fuel over consumption, but it also can fill the understanding in relation to potential pollution impacts. Antifouling coating debris released during cleaning carries plastic and toxic heavy metal pollution. With capture systems, the intake of water and captured materials can be assessed to indicate the level of pollution that would otherwise be released into the port. This type of data can help to take the guess work and assumptions out of decision making around managing biofouling risks.

With more information able to be fed from in-water cleaning with full capture systems, the data gap can be lessened and help to reduce the decision paralysis surrounding the regulation of in-water cleaning of ship hulls. This again takes openness and collaboration from industry to become a reality but can certainly speed up the momentum toward fit-for-purpose regulations, and therefore the reduction in the negative impacts of biofouling on vessels around the world.

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Monitoring and Mapping of Invasive Aquatic Species Transported with Shipping as Vector

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Abstract

Shipping facilitates the transfer of aquatic organisms between different sea areas and enables invasive species to cross their natural dispersion limits. In this work we illustrate possible ways to trace and predict species invasions using ship traffic data. First, we exemplify with two sea squirts (growing attached to surfaces and ship hulls), by tracing back the traffic pattern at the time of their introduction. Secondly, the motile blue crab is used as an example to identify the data and information needed to predict possible locations for coming invasions. The cases are based on i) historical ship traffic data from Automated Information System (AIS) ii) recent or expected invaders for a certain location and iii) ports in the Northeast Atlantic with high risk for receiving invasive species. Within the growing and dynamic shipping industry both routes and number of ships for specific routes will change over time which also is illustrated in this work. In the end we summarize parameters that needs to be considered for work with ship traffic-based predictions of invasive species.

1. Introduction

Generally, global shipping increases in frequency and connectivity as well as liner size, *Hoffmann et al. (2017)*. Biofouling on ships is shown to be responsible for a large share (56 – 69 %) of coastal transfers of Non Indigenous Species worldwide, *Galil et al. (2019)*. The relatively short transfer time of ships can transport marine organisms fast enough to survive and still be viable upon arrival in new areas. Highly connected ports are frequented by vessels from different geographical regions, and therefore possibly receive both a high number and variety of potential invaders. Ports, as the arrival place of potential invasives, are globally characterized with hard substrate, sheltered environmental conditions and high pollution. Hence, increasing shipping connectivity leads to more introductions of potential pest species in ecosystems that are already weakened due to heavy human alteration and climate change. The establishment of non-native species is favored by an impacted ecosystem, where declining biodiversity make the systems more vulnerable. The species present in the departure port are likely to survive and be successful in an arrival port with similar salinity and temperature range, *Gollasch and Leppäkoski (2007)*. From there secondary spread, either by stepping stones like jetties or other artificial structures, or as biofouling on ships in local traffic and leisure boats is possible.

The marine species can be transferred to new areas via shipping in three ways, either in ballast water, as attached to the hull or associated with specific hull structures, *Schimanski et al. (2017)*. Within ships ballast water species are transferred in their small larval stages as free-swimming plankton. The IMO Ballast Water Management Convention (valid for existing ships from September 2024) aim to minimize the transfer of these planktonic stages. Regarding measures to control biofouling, the IMO Biofouling guidelines were updated 2023, except the part regarding In Water Hull Cleaning (where work is ongoing in 2024). In addition to biofouling on the flat hull surfaces, special structures or areas, so-called niche areas of ships are considered hotspots for transfer of aquatic organisms, however not yet much studied, *Davidson et al. (2009), Coutts et al. (2010)*.

Financially speaking, species invasions have different cost points:

1. Cost for loss of Ecosystem services, such as limiting protection of the coastline by for example seagrass meadows, which also act as nurseries for fish, that later contribute to fishery, predation on commercial fish etc.
2. Cleaning costs, such as in water hull cleaning to ensure performance of ship in terms of speed and maneuverability or cleaning of cooling water intakes used by various industries.
3. Eradication and management costs (ie restoration of habitats, harvesting)

To avoid cost and damage to the marine ecosystems, fast detection, and early measures to hinder further spread of the species is key. Efforts after establishment, if even possible, will be both time consuming and costly. To visually detect new species in the marine environment is however a challenge and much more difficult to follow compared to an introduction on land.

Today monitoring of marine environments is conducted on a national basis where programs vary between countries both in number of sampling stations, frequency and methods used. Various tools that enhance reporting of new species as regional/or national platforms severely benefit an efficient management of invasive species. Citizen reporting of invasive species has proven successful in several countries, *Lehtiniemi et al. (2020).* Within these systems citizen observers report the sighting of species (place and date), which is validated by taxonomic experts and reported into national databases. Databases for species distribution spanning over larger geographical areas can be used to find so called "door knocking species" to specific countries or regions (ie species that are not present yet but likely to arrive in a near future). Examples of species distribution databases are WORMS (mainly used in this study) AquaNIS and gbif (links provided in references).

According to EU-Marine Strategy Framework Directive (MSFD) each member state in EU has to consider Non-Indigenous Species (NIS) in their management strategies. The Non-Indigenous Species treated under Descriptor D2 includes one primary criterion (D2C1: new NIS introductions) and within six-year cycles each member state are obliged to reports the status (i.e. if Good Environmental Status is reached) for each water basin. In regard to shipping and to provide a globally consistent approach to manage biofouling on ship hulls the above-mentioned IMO Biofouling guidelines (2023) are available, as a guidance. This can be compared to the IMO Ballast Water Management Convention, in force from September 2024, which strictly require that all ships in international trade treat the ballast water before discharge. The global IMO regulations are developed to "protect" different countries from new introductions of invasive species. In our examples, we follow the current administrative setup of invasive species mitigation, taking on national (in this case Norwegian and Swedish) perspectives. However, as marine organisms do not sense or detect any borders, the current national approaches could be improved by instead or in addition using regional areas or water basins, considering geographic and oceanographic parameters.

2. Tracing back invasive species - possibilities to mitigate species invasions using shipping data

The examples presented are selected based on i) species known to have shipping as vector for transfer ii) port of first arrival for the specific invader is located in a prior uninfected geographic area.

The aim for the first two examples was to investigate if changes in shipping patterns can be used for predictions of new NIS arrivals and serve as basis for future rapid mitigation of NIS invasions. The two well-known invasive tunicates *Didemnum vexillium* (sea carpet) and *Styela clava* (club tunicate) were from their respective time of invasion traced back by analyzing historical AIS data.

In the example with the crab *Callinectes sapidus* (blue crab) we instead reason on how to use shipping routes and patterns as a measure to predict future plausible or "risky" ports for arrival.

2.1. Example sea carpet tunicate *Didemnum vexillium* to Engøysundet, Stavanger, Norway

Didemnum vexillium originally native to Japan, recently has been recorded as established over the west coast of Scandinavia, where it first arrived in Engøysundet in Stavanger (Norway) in 2020, Fig.1. *D.*

vexillium is growing and spread as (carpet like) colonies and shown to be transported over 100 km *Fletcher et al. (2013)*. *D. vexillum* rapidly overgrows rocks, shellfish, and other organisms (e.g. sponges, hydroids, tunicates, algae) and has the potential to cause economic damage to fisheries and aquaculture. It can also have negative ecological impacts and in some areas its rapid expansion has reduced the abundance of previously established benthic species like for example the blue mussel *Mytilus edulis, Auker (2010)*. *D. vexillium* is preliminarily associated with pontoons, platforms, and ships and boats with long inactive times in ports, *Manson and Brown (2011),* therefore it is hypothesized to travel with slow moving big structures such as towed jetties, as well as leisure boats.

Transactions from 55 ports, Fig.1, within the distribution area of *D. vexillium* were used for the analysis of potential shipping vector of invasion to Norway. Shipping data (Sea-Web database) from 2018-2020 including transits from British Isles to Engøysundet, Stavanger, were analyzed to identify changes in patterns or intensity that could be associated with the invasion event in 2020.

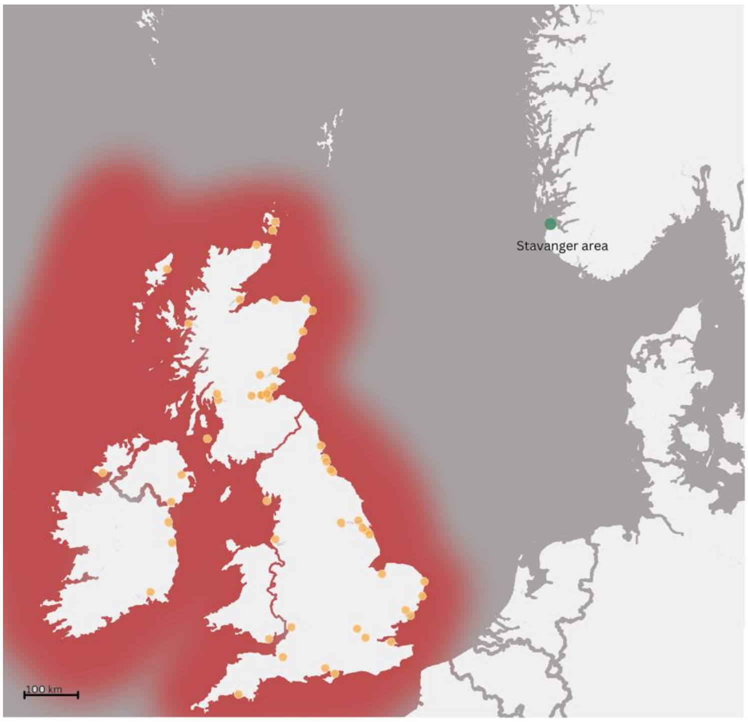

Fig.1: Shipping as potential vector for *Didemnum vexillium* invasion to Norway: *D. vexillium* was first observed in Stavanger area, transactions from ports (marked in orange) to Stavanger area, within the distribution range (marked red) in the years 2018-2020 were analyzed to identify changes in patterns or intensity that could be associated with the invasion event in 2020.

In a selected smaller set of data, including only the most likely vessel type to carry *D. vexillium,* pontoon-like structures, the transactions from the infected coastline of the British Isles increased gradually from three in 2017, six in 2018 to nine in 2019, Fig.2. The total number of transits are in total 14, where pipelayer crane ship was the most abundant. Establishment of new species has shown to occur even with an initial low concentration of invasive individuals, *Clarke and Therriault (n.d.), Lange and Marshall (2016)*. With these few ships, it could potentially be interesting to investigate the cleaning records of the distinct vessels both in regard to find traces of *D. vexillium* and (if cleaning not was performed) advice on that for the future.

Additionally, there was seen to be a variation in number of ships in traffic to Stavanger between the years for the different ports in the British Isles (Figure 3), with some ports having departure during all three years, some two of the years and others only a single year. The insecurity due to a lack of high-resolution distribution data of *D. vexillium* in the actual ports, could, in combination with the varying spatial departure pattern, make it difficult to predict invasion risk.

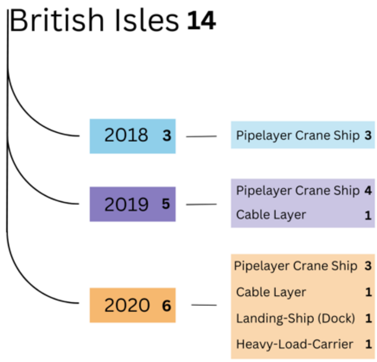

Fig.2: Changes in shipping intensity of potential high-risk ships and structures for D. *vexillium* invasion: including all ships that inhabit pontoon/platform like structures, the 14 transactions from the area of *D. vexillium* distribution around the British Isles are divided by year and ship type. 2018 (three): three pipelayer crane ships, 2019 (six) four pipelayer crane ships, and one cable layer, 2020 (nine): three pipelayer crane ships, one cable layer, one Dock, and one Heavy Load Carrier.

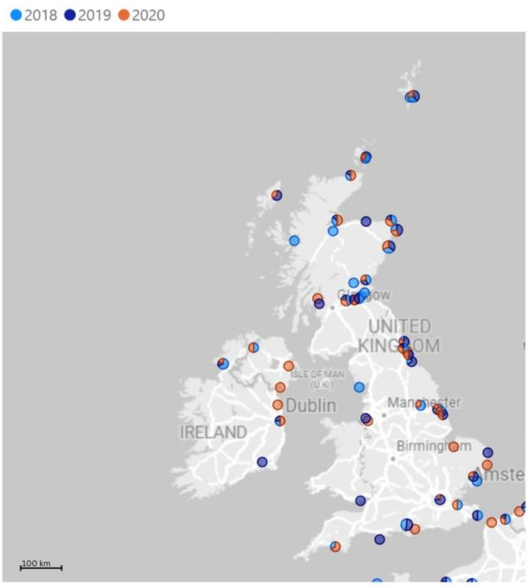

Fig.3: Variation in departures to Stavanger between the years for the different British Isles ports: Ports of origin to Stavanger Area, over the Years 2018 (light blue), 2019 (dark blue), 2020 (orange).

2.2. Example club tunicate *Styela clava* to Brofjorden, Lysekil, Swedish Westcoast

With *Styela Clava* being present at the British Isles, as well as in more temperate regions like the west coast of Spain, Portugal and Marocco (WORMS), Fig.4, its spread towards other places with matching habitats is inevitable. *S. clava* grows rapidly and can quickly reach high densities, i.e. compete with present communities for food and space. While there is some knowledge about the settlement preferences of S. *clava* and other tunicates on antifouling paints, *Locke et al. (2009),* species specific preferences concerning vessel types are unknown.

Transactions were analyzed using AIS data from 2016 to 2024 from potentially infested ports in the North East Atlantic Area including British Isles, France, Portugal, and the west coast of Spain to Brofjorden area, where S. *clava* was first recorded in Sweden 2022 (Rappen). In 2017, 181 vessels to Brofjorden area were recorded, the transactions then decreased gradually to 64 vessels in 2023. Transaction based on the total fleet were not found as indicator for this invasion event and information of *S. clava* preferences for ship types are lacking, why further processing not was possible. However (as also written above) a small number of infected vessels, even down to one, can cause the establishment of an invasive species. The countries bordering to Sweden (Denmark and Norway) were not included as potential donor areas in this analysis as natural spread (ocean currents) and secondary spread (local shipping and leisure boating) also are considered as possible vectors.

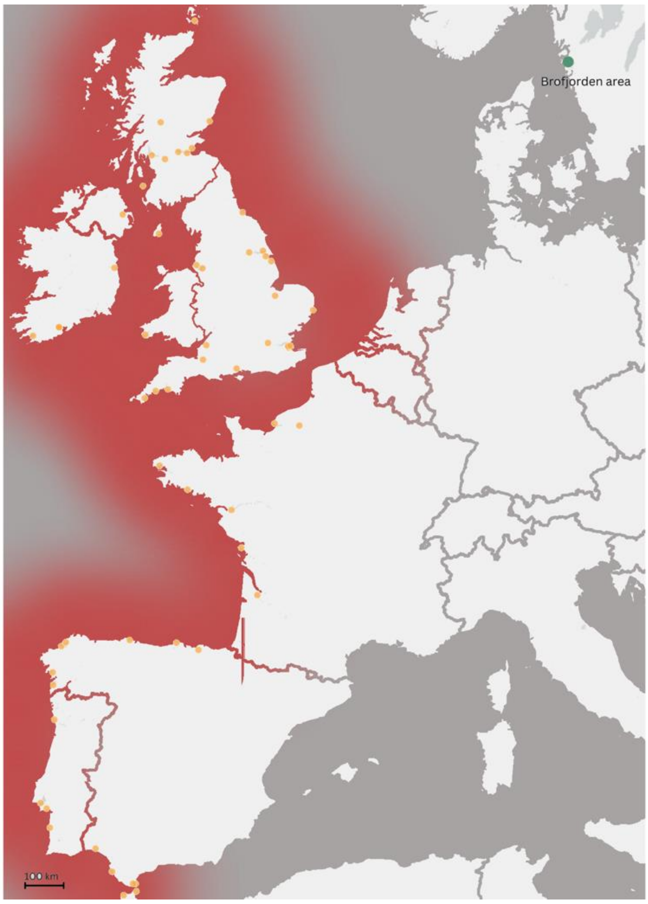

Fig.4: Ports of origin (orange dots) used for the analysis of potential shipping vector for Styela clava invasion to Sweden: S. clava was first observed in Brofjorden area (marked in green), transactions from ports (marked in orange) to Brofjorden area, within the distribution range (marked red) of the Years 2017-2023 were analyzed to identify changes in patterns or intensity that could be associated with the invasion event in 2022.

2.3. Example Predict *Callinectes sapidus* first arrival to Sweden

The blue crab is here used as an example of how to use shipping patterns as a management tool in predicting invasions. First present in Europe in 1901, the blue crab is now present in seven of the nine south European marine ecoregions (the Mediterranean Sea), after a rapid extension of the species from 2010, *Clavero et al. (2022)*. Mating and nursing of *C. sapidus* is done in low salinity environments and survival and reproduction are impacted in temperatures below 10°, *Serc et al. (2007).* Global warming with rising temperatures in the Baltic Sea and Kattegat-Skagerrak Area (Swedish coasts) could therefor lead to increase in favorable conditions for *C. sapidus*. Adult individuals of the blue crab can potentially travel in niche areas, and on heavily fouled hulls, *Nehring et al. (2011)*, while larvae have been found in high concentrations in cooling and ballast water, *Galil et al. (2006), Nehring et al. (2011)*. *C. sapidus* can function as a so-called keystone species in the invaded ecosystems, leading to that native species like the green crab reduce drastically in abundance, and the ecosystem is instead shaped by the new species, *Clavero et al. (2022).* The potential invasion to Swedish waters and especially the Baltic Sea therefore could lead to severe impacts on ecosystems, ecosystem functions and fishery resources. Since *C. sapidus* is an impactful invader in the Mediterranean, management plans of mitigation and eradication are tested and known, *Marchessaux et al. (2023),* such as preventive catching pots close to high-risk ports, *Cerri et al. (2020),* specific hull-cleaning methods on high-risk transfers and an increase in fishing pressure on the blue crab in already infected areas. Knowledge about the connectivity of invasive species populations is key (see above) in management actions, *Hulme (2006),* and for *C. sapidus* until now mostly unknown. Wider screenings and specification of potential vectors of invasion, such as vessel type, may lead to higher success probabilities in mitigation of establishment of *C. sapidus* in Swedish waters and the Baltic Sea, *Mancinelli et al. (2017). C. sapidus* stands as an example of a species whose invasion to Swedish waters can potentially be mitigated, if specific monitoring and preventive low impact measures are implemented. Research that provides detailed information on biological traits, in combination with shipping analysis and suggestions of action plans to authorities are needed.

2.4. Result summary

For the sea carpet an increase in traffic from the infested area coincided in time with the first finding of the species at the Norwegian west coast. The analysis was based on specific ship types considered to facilitate transfer of the sea carpet. For the club tunicate, instead the total number of vessels arriving from the identified risk area was used and it was shown to decrease during the time period of interest. Data on what ship types most likely to transfer the specific species is crucial for the analyses.

For the blue crab and other so called “door knocking species” (not yet in area of interest but detected in nearby areas) frequent monitoring and updated, comprehensive and accessible distribution data is key to prevent future invasions.

3. Discussion and conclusion

To enable tracing back of invasion events will require thorough knowledge about the specific species of interest as well as the shipping vector. Data needed for species are in addition to the distribution range and first recordings also the so-called biological traits like temperature and salinity limits, reproduction and spread, habitat preferences etc. To identify high-risk vessels, ports and pathways, the vessel characteristics and shipping patterns are needed. Predicting invasions using AIS data of ship traffic is therefore possible if enough data about both species of interest, transfer and port att risk is present.

Adding known invaders like the blue crab to EU monitoring and making the data available in a comprehensive and accessible way, is key to prevent future invasions. Port monitoring with traditional identification methods are time-consuming and costly, and in addition is the taxonomic expertise getting more difficult to reach. The use of molecular techniques in monitoring is therefore timely, and with eDNA can for example water samples be used to identify the species present.

While this study only focused on importance of shipping as vector also other ways of introduction like aquaculture should optimally be included for a more complete picture of invasions. Also, secondary spread with local traffic and leisure boating needs to be described as well as the importance of natural spread with ocean currents setting the dispersal limits for specific species.

In conclusion, to identify high-risk vessels, ports, and pathways, preventing future invasions, following information should be investigated:

i. The potential invasive species habitat requirements and tolerance in transport
ii. The potential invasive species preferred invasion vector
iii. The species distribution (updated data)
iv. Ecological habitats of connected ports
v. Vessel characteristics, such as presence of niche areas, hull cleaning protocols, etc
vi. Shipping patterns between ports in infected areas and non-infected areas

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Proposed Revisions to the IMCA D082 Guidelines for Simultaneous ROV and Diving Operations

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Abstract

This article explores revisions to the IMCA D082 guideline to integrate ROV operations alongside traditional diving in underwater ship husbandry. As ROVs become more prevalent, the need for updated safety protocols in combined operations is essential. The article highlights key risks, such as collision and entanglement, and provides recommendations for improving safety, including risk assessments, communication, and real-time monitoring. Drawing from the IMCA D054 standard for offshore operations, these revisions aim to ensure safer and more efficient collaboration between ROV and diving operations.

1. Introduction

The International Marine Contractors Association (IMCA) developed the IMCA D082: Guidance on Diving Operations in Support of Underwater Ship Husbandry to provide a comprehensive framework for conducting underwater ship husbandry (UWSH) activities safely and effectively. The primary focus of the document is on diving operations, covering essential procedures for inspection, maintenance, and repair of vessels' hulls and underwater appendages.

The guidance details the roles and responsibilities of all parties involved, including vessel owners, managers, diving contractors, and support personnel. It provides best practices for selecting competent diving contractors and emphasizes the importance of proper risk assessment, planning, and coordination between various stakeholders. The document is primarily intended to ensure safe UWSH diving projects and outlines the necessary qualifications for dive teams, safety procedures, and the use of appropriate equipment.

Although focused on surface-supplied diving operations, the guideline also touches upon the involvement of support personnel, such as those operating Remotely Operated Vehicles (ROVs), particularly where divers cannot safely perform tasks.

Overall, IMCA D082 serves as a key reference to improve the safety and efficiency of UWSH diving operations, promoting industry-wide standards to mitigate hazards and enhance operational outcomes.

In recent years, there has been a marked increase in the development and commercial utilization of Remotely Operated Vehicles (ROVs) for performing underwater ship husbandry tasks. These robotic systems are designed to handle a significant portion of hull cleaning, reducing the need for diving work. ROVs offer several advantages over traditional diving operations, including enhanced safety, consistent quality, and greater operational efficiency. However, despite the growing adoption of ROVs, diving operations remain essential for performing repairs and cleaning in complex or niche areas such as propellers, sea chests, rudders, and bilge keels, where robotic systems may be less effective.

As the use of robotic technology continues to expand and becomes an industry standard in ship husbandry, this paper proposes recommendations for a revised edition of the IMCA D082 guidelines. Specifically, it suggests the integration of ROV operations into the standard, reflecting their increasing role in underwater ship maintenance. Incorporating ROV usage into the IMCA D082 guidelines will better align the document with current industry practices, ensuring that it remains relevant and supports the safe, efficient, and effective execution of UWSH activities using both traditional diving methods and modern robotic technologies.

Additionally, elements from the IMCA D054 standard, which is designed for the offshore industry to guide the safe operation of ROVs in combination with divers in the same underwater space, can be applied to the IMCA D082 guideline. Incorporating relevant practices from IMCA D054 would enhance IMCA D082 by improving the coordination between ROVs and divers, ensuring safer and more efficient operations in underwater ship husbandry. This integration would align the revised guideline with current industry practices and promote the effective collaboration of both robotic and human capabilities.

2. Examples of simultaneous operation

Examples of simultaneous operation between ROV and diving activities are regularly conducted in various configurations, reflecting the versatility of both technologies in different operational settings. These combinations include:

- Diving operations from one workboat and ROV operations from another workboat (e.g., C-leanship).
- Diving and ROV operations conducted from the same workboat (e.g., Cleanhull).
- Diving operations from shore and ROV operations from a workboat (e.g., Fleet Cleaner).
- Diving and ROV operations conducted from shore (e.g., Ecosubsea).
- Diving operations from a workboat and ROV operations from the sea vessel (e.g., Jotun Hullskater).

These examples illustrate the flexibility of combining ROV and diver operations to address specific underwater ship husbandry tasks, further emphasizing the need for integrated guidelines in the revised IMCA D082.

3. Risks of simultaneous operation

The integration of ROV and diving operations in underwater ship husbandry presents a range of potential risks that must be carefully considered to ensure the safety of personnel and equipment. While not exhaustive, the following risks highlight key concerns that should be addressed by the working group revising the IMCA D082 guidelines:

- Collision or entanglement risks: The possibility of the diver or their umbilical being hit by the ROV or becoming entangled with it.
- Falling object hazards: The risk of the diver or umbilical being struck or trapped by falling objects from the ROV support vessel.
- Vessel-related dangers: The risk of the diver or umbilical becoming entangled in the propeller of the ROV support vessel.
- Fluid and pressure hazards: The potential for high-pressure fluid leaks from the ROV or its umbilical near the diver, posing significant danger.
- Electrical risks: The possibility of electrocution due to insulation failure in the ROV, which could threaten diver safety.
- Eye damage: The potential for visual damage to the diver from direct exposure to the ROV's lighting or camera systems.
- Visibility issues: The disturbance of sediment by the ROV, leading to reduced visibility and operational difficulty for divers.
- Noise pollution: The generation of disruptive noise by the ROV, which could impair communication and cause discomfort or harm to divers.

Addressing these risks is essential for the development of comprehensive safety protocols in the revised IMCA D082 guideline, ensuring safe and effective collaboration between ROV and diving operations in underwater ship husbandry.

4. Recommendations for the IMCA D082 guideline

The following recommendations are proposed for the working group revising the IMCA D082 guideline to enhance safety in the simultaneous operation of ROV and diving operations during underwater ship husbandry services:

1. A comprehensive risk assessment must be conducted prior to the commencement of any underwater operation to identify potential hazards and implement mitigation strategies.
2. Both the ROV and diving teams should undergo thorough training and familiarization with the procedures specific to simultaneous operations, ensuring proficiency and safety in the collaborative environment.
3. A continuous and reliable communication channel should be maintained between the Diving Supervisor and ROV Supervisor throughout the operation to facilitate effective coordination and response to any emerging issues.
4. The Diving Supervisor must have operational command in all combined operations, retaining full authority over the ROV Supervisor to ensure diver safety remains the primary focus.
5. A defined safety distance between the ROV and diving operations must be established. It is recommended to maintain a minimum distance of 50 meters to minimize the risk of collisions or entanglements.
6. A tag-out/lock-out procedure for the ROV support vessel should be implemented when the vessel is moored in the diving zone to prevent any unintended movement or activation of the vessel that could endanger the divers.
7. A safety meeting, including a detailed pre-dive briefing, should be conducted prior to any simultaneous operation. This should cover interaction protocols between the ROV and divers, safety zones, expected movements, and specific operational parameters, ensuring all personnel are aware of the procedures and potential risks.
8. Emergency protocols should be clearly defined and regularly rehearsed, including the immediate retrieval of divers or ROVs in case of an incident. Both teams must be familiar with emergency evacuation and rescue procedures.
9. Real-time monitoring of both ROV and diver positions should be employed using advanced tracking systems to maintain situational awareness and avoid proximity hazards.

These enhanced recommendations would further solidify the IMCA D082 guideline, ensuring a safer and more efficient integration of ROV and diving operations in underwater ship husbandry.

Acknowledgement

We sincerely thank the IMCA D082 workgroup members for their invaluable contributions. Their dedication and efforts have greatly enhanced the safety standards in our industry. We would also like to thank professor Volker Betram for organizing the PortPIC event to share valuable information within the industry.

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Evaluating Biofouling Management Strategies: Balancing Marine Environmental Protection and GHG Emissions

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Abstract

The purpose of this research is to support industry practitioners with comparing alternative biofouling management strategies. We present a framework for evaluating antifouling products and extend our previous work on energy efficiency with the introduction of new variables related to water discharges in addition to fuel consumption and GHG emissions. The paper models the impact of different biofouling management strategies for a bulk carrier focusing on total copper release to water based on the selection of coating and hull cleaning practices. Our findings suggest that a silicone-based coating with organic biocides provides the best option to optimize fuel savings and discharges to the water column. Our results inform market and policy actors towards more sustainable practices, thereby contributing to the broader goal of reducing energy demand without compromising the marine environment.

1. Introduction

Energy efficiency measures are a critical mechanism to ensure the marine industry remains in the right decarbonization paths to achieve the ambitious targets set forth by the IMO. Retaining a clean and smooth hull, free of biofouling growth, ensures optimal hydrodynamics which in turn can significantly reduce the energy demand of the global fleet. Beyond energy efficiency, keeping ship hulls clean and appropriately managing hull biofouling growth is critical to the preservation of marine biodiversity. This is exemplified in the recent review and update of the IMO guidelines for the control and management of ships' biofouling which aim to minimize the transfer of invasive aquatic species, *IMO (2023)*. Together with ballast water, biofouling on ship hulls is considered the largest vector for the introduction of invasive aquatic species, *Bailey et al. (2020), Williams et al. (2013).*

A primary consideration when choosing a biofouling management strategy is centered on the choice of antifouling coating system and the corresponding maintenance requirements during its lifetime in the form of in-water hull cleaning. Such choices have an considerable impact on ship energy efficiency, the prevention of invasive species translocation via ship hulls, and are a key factor in determining the release of waste substances to the marine environment. With this paper we argue that the strategic and operational choices entailed in biofouling management will need to balance the trade-offs between emissions to air (i.e. reduction of energy demand from clean hulls) and emissions to water (passive or accelerated release of waste substances to ensure a clean hull).

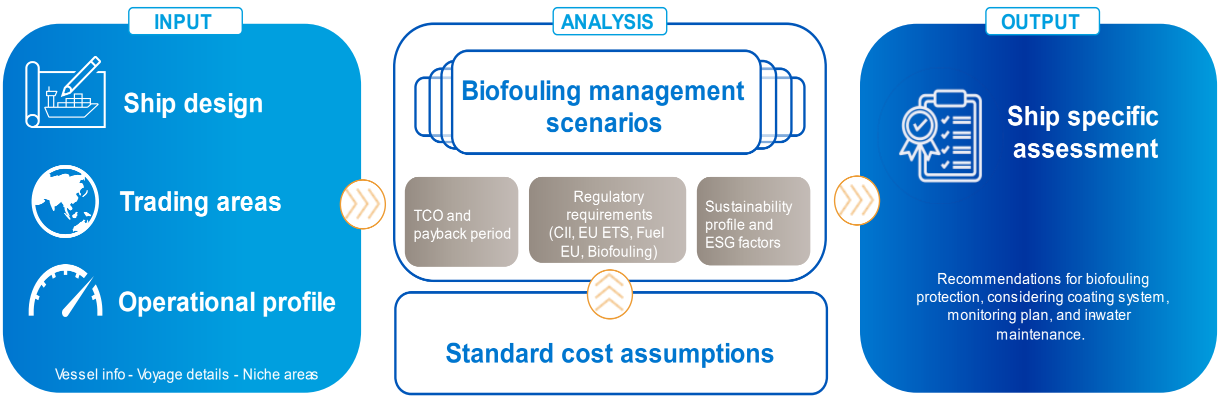

Fig.1: Hempel Framework for evaluating biofouling management scenarios

Sfiris et al. (2023) presented a decision framework, Fig.1, and examined the impact of alternative biofouling management strategies on energy efficiency (fuel consumption and carbon intensity rating) for a vessel case study. With this paper we extend our previous work on energy efficiency to provide a quantitative analysis of total copper emissions to water as a result of alternative biofouling management strategies. This allows us to address some of the limitations of our previous work and promote a more wholistic approach that considers both GHG emissions and waste substances to the water.

3. Case study

This paper builds upon the case study presented in *Sfiris et al. (2023)*, which itself expanded on the analysis from *GEF-UNDP-IMO (2022)* on a bulk carrier coated with a Self-Polishing Coating (SPC) system, as previously studied by *Uzun et al. (2019)*. *GEF-UNDP-IMO (2022)* investigated the potential for greenhouse gas (GHG) reduction through three biofouling management scenarios:

1) using only SPC without any in-water cleaning (baseline scenario),
2) using an SPC with responsive cleaning, and
3) using an SPC with regular cleaning.

The study evaluated the impact of these scenarios on the ship's required power, fuel consumption, fuel costs, and total CO_2 emissions over a 5-year docking cycle. The study demonstrated the GHG reduction potential of regular cleaning on SPC coated hulls. However, *GEF-UNDP-IMO (2022)* exclusively considered SPC-type coatings in all scenarios and did not account for any other costs or impacts associated with biofouling management activities.

Building on this analysis, *Sfiris et al. (2023)* introduced a silicone-based low-friction coating into the investigation and expanded the scope with a fourth scenario. This expanded approach evaluated the impact of the selected biofouling management strategies on total fuel consumption, CII rating variations, EU ETS carbon costs, and Total Cost of Ownership (TCO), including payback periods over a 5-year docking cycle. This study provided a more holistic overview on the impact on antifouling coatings on energy efficiency and shed light on the benefits of the latest silicone-based antifouling coating technologies. However, it did not consider the impact to the water column resulting from alternative biofouling management choices. To fill this gap, our paper expands on the work of *Sfiris et al. (2023)* by providing a quantitative analysis of total copper release to water from the two best-performing alternative biofouling management strategies in terms of fuel efficiency: Scenario 3, which involves SPC with regular cleaning, and Scenario 4, which refers to a silicone-based low-friction coating with no in-water hull cleaning. Scenario 1, which involves an SPC system with no in-water cleaning is still used as a baseline for comparison. Looking into the topic of water emissions enables us to address the limitations of our previous study and offer a more comprehensive evaluation of biofouling management options, taking into account both GHG emissions and waterborne waste substances. Table I shows the principal particulars and selected biofouling management scenarios for the case vessel.

Table I: Principal particulars and selected biofouling management scenarios of the target vessel, adapted from *GEF-UNDP-IMO (2022)*

<table>
<tr><td>Vessel type</td><td>Bulk carrier</td><td>Fuel consumption (clean - SPC)</td><td>20.4 t/day</td></tr>
<tr><td>Deadweight</td><td>40,000 t</td><td>Operating region</td><td>Mediterranean</td></tr>
<tr><td>Length</td><td>179.00 m</td><td>Operation period</td><td>5 years</td></tr>
<tr><td>Breadth</td><td>28.00 m</td><td rowspan="4">Biofouling management scenarios</td><td rowspan="4">Scenario 1: SPC - no in-water cleaning
Scenario 3: SPC + regular cleaning
Scenario 4: Silicone-based fouling-release coating with organic biocides - no in-water hull cleaning</td></tr>
<tr><td>Design draft</td><td>10.60 m</td></tr>
<tr><td>Wetted surface area</td><td>7,350 m²</td></tr>
<tr><td>Speed</td><td>14 kn</td></tr>
</table>

3.1. Assumptions

All scenarios are replicated from the study by *Sfiris et al. (2023)*, utilizing the same assumptions. The analysis assumes that the ship undergoes dry-docking and implements the specified biofouling management strategies.

3.1.1. Biofouling management assumptions

Table II shows the assumptions used for the analyzed biofouling management scenarios, and Table III shows the details of the assumptions used for the present study.

Table II: The analyzed biofouling management scenarios and assumptions used

Biofouling management scenarios	Hull coating	Hull related measures	Propeller related measures
Scenario 1 (baseline)	Self-polishing antifouling coating	No	No
Scenario 3	Self-polishing antifouling coating	Hull cleaning after 1 ½, 2, 2 ½, 3, 3 ½, 4, 4 ½ years	Propeller cleaning after 1 ½, 2, 2 ½, 3, 3 ½, 4, 4 ½ years
Scenario 4	Silicone-based fouling release coating with organic biocides	No	Propeller polishing, twice a year

3.1.2. Copper emissions to water

In this section, we aimed to select an indicator that facilitates straightforward comparison of findings and is well-documented in the literature. Therefore, we chose total copper (Cu) release as a measure of emissions to water.

According to *Morrisey et al. (2013)* and to the best of our knowledge, there is a close relationship between the level of biofouling on a surface, the strength of cleaning, and the subsequent emissions to water. The following excerpt from *Morrisey et al. (2013)* illustrates the copper release to the water when conducting in-water hull cleaning of hull with a market average SPC coating:

"The total removal depths during in-water cleaning are not well established. For light cleaning with a soft cloth or brush, *Anderson (1993)* suggested a depth of 25 µm, which would remove the biofilm or slime layer and soft fouling. For more intensive cleaning with a hard brush to remove hard fouling, *Anderson (1993), Forbes (1996),* and *Ingle (2006)* provided estimates ranging from 12.5 to 100 µm. For this assessment, an upper estimate of 75 µm was used to represent a realistic worst-case scenario (not the absolute worst possible case)." (pg. 130)

Table III: The impact of hull cleaning on copper release, adapted from *Morrisey et al. (2013)*

	Commercial vessels
	SPC
Copper release from light cleaning (µg/cm^2)	
Lower estimate	85
Upper estimate	625
Copper release from aggressive cleaning (µg/cm^2)	
Lower estimate	3145
Upper estimate	4225

Given the lack of current data in the industry regarding the impact of copper release from in-water cleaning activities, we sponsored an independent marine research institute to conduct in-water hull cleaning simulations and report back on various waste substances discharged. The contractor developed a custom methodology and test setup to analyze various parameters and coating systems. The results were aligned with the insights shared by Morrisey et al. (2013), namely in cases of microfouling cleaning for a market average SPC coating (i.e. regular cleaning with soft brushes) the copper release was 85.7 $\mu g/cm^2$ – which is also the number we finally used for our simulation in this paper. This assumption aligns with the *GEF-UNDP-IMO (2022)*, which predicted only limited fouling accumulation on the hull before each cleaning took place.

In our analysis, we assume a constant copper release as a result of in-water hull cleaning throughout all cleaning interventions. In reality, each hull cleaning job is expected to further reduce the efficacy of the coating system and thus have an impact on the release of copper and other materials throughout the 5 years in-service period. For a complete list of assumptions related to in-water hull cleaning, *Sfiris et al. (2013).*

3.2. Results

Scenario 1 (SPC - no in-water cleaning) results in a copper release of 588.78 kg, serving as the baseline for comparison. In Scenario 3 (SPC + regular cleaning), copper release increases by 7.5% to 632.868 kg, highlighting the environmental impact of regular cleaning on copper emissions, despite its effectiveness in maintaining hull cleanliness. Conversely, Scenario 4 (Silicone-based low friction coating - no in-water hull cleaning) significantly reduces copper release to 15.355 kg, representing a 97.39% decrease compared to Scenario 1. This substantial reduction indicates that silicone-based coatings, even with limited biocide, can effectively mitigate copper pollution in the marine environment.

In terms of CO_2 emissions, Scenario 1 (SPC - no in-water cleaning) produces the highest output at 145,043 tons, establishing the baseline for CO2 emissions. Scenario 3 (SPC + regular cleaning) reduces CO_2 emissions by 18.35%, bringing them down to 118,425 tons. However, this reduction in CO_2 comes at the cost of increased copper emissions. Scenario 4 (Silicone-based low friction coating - no in-water hull cleaning) achieves the most significant reduction in CO_2 emissions, with a 25.18% decrease to 108,517 tons. This scenario not only minimizes copper release but also substantially lowers CO2 emissions, making it the most environmentally sustainable option overall. The findings are demonstrated in Table IV and Fig.2.

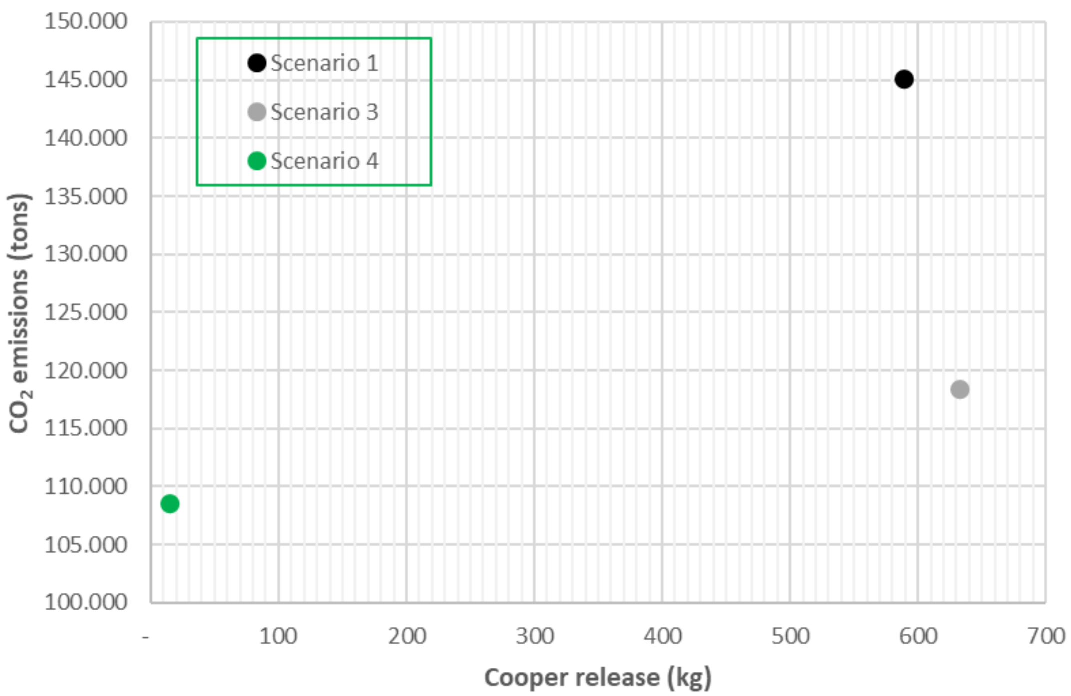

Fig.2: Impact of biofouling management method on total Cu emissions to water and CO_2 emission

Table IV: The impact of biofouling management methods on the Cu emissions to water and CO2 emission to air

Biofouling management scenario	Total Cooper release (kg)	Δ copper (to Scenario 1)	CO_2 emissions*	Δ CO_2 (to Scenario 1)
Scenario 1	588.780 kg	-	145043 t	-
Scenario 3	632.868 kg	7.48%	118425 t	-18.35%
Scenario 4	15.355 kg	-97.39%	108517 t	-25.18%

*Adapted from *Sfiris et al. (2023).*

The analysis exemplifies the need for industry stakeholders to consider copper release and CO_2 emissions when making biofouling management choices. Although SPCs coatings in combination with regular hull cleaning can offer a reduction in CO_2 emissions (Scenario 3), such choices will have an impact to marine ecosystems. Especially when conducted without a capture system, in-water hull cleaning may also increase the risk of introducing invasive aquatic species.

In our analysis, scenario 4 emerges as the most balanced approach, effectively reducing both types of emissions and presenting a strong case for adopting silicone-based coatings with organic biocides in biofouling management strategies.

The copper emission estimates provided in this study are based on the assumption that in-water hull cleaning is performed correctly - using the right brush type and being executed by skilled divers/ROV operators under normal environmental conditions. However, deviations from this ideal scenario, such as using an incorrect brush, unexpected environmental factors like strong currents or waves, or a diver's lack of experience, can dramatically increase copper emissions and damage the coating system. Table III illustrates how significantly copper emissions can spike depending on the intensity of cleaning. The frequency of cleaning also increases the likelihood of accelerated cooper release, making it essential to consider these risks when evaluating in-water hull cleaning as an option. Therefore, while the quantitative values presented here serve as a comparative tool, they are not absolute and should be interpreted with caution.

Similarly, even silicone-based coatings, which typically require no in-water cleaning, could face unexpected biofouling accumulation events, leading operators to consider one or two cleaning sessions. If this were to happen, the resulting copper emissions would only increase by 0.35 kg, bringing the total to 15.70 kg over the 5-year docking cycle—a mere 2.27% increase compared to Scenario 4, still representing a -97.33% decrease compared to Scenario 1. While this impact is minimal, it underscores the importance of exercising extreme caution during cleaning to avoid damaging the coating, which could accelerate refouling rates, increase the need for frequent cleanings, and result in higher fuel consumption due to these unintended consequences.

4. Conclusions and discussion

The analysis conducted in this study provides a nuanced understanding of the environmental trade-offs associated with different biofouling management strategies. The findings highlight the complex relationship between copper emissions to water and CO2 emissions to air, demonstrating that strategies that are effective in one domain may have unintended consequences in another.

Scenario 3, which involves regular in-water cleaning of a Self-Polishing Coating (SPC), can considerably increase copper emissions to the water column compared to the baseline Scenario 1 (SPC with no in-water cleaning). This finding is consistent with previous studies that suggest in-water cleaning accelerates the release of copper from antifouling coatings due to the mechanical removal of biofouling along with the top layers of the coating. The 7.5% increase in copper emissions underscores the environmental costs of maintaining a clean hull through regular cleaning, raising concerns about the increasing impact in marine ecosystems. In contrast, Scenario 4, which utilizes a silicone-based low-friction coating with no in-water cleaning, shows a dramatic reduction in copper release, demonstrating the effectiveness of silicone-based coatings in mitigating copper pollution. The 97.39% decrease in copper emissions compared to the baseline is particularly noteworthy, suggesting that silicone-based coatings could be a viable solution for reducing the environmental footprint of shipping operations.

In terms of CO_2 emissions, Scenario 3 offers a clear reduction relative to Scenario 1, due to the improved hydrodynamic efficiency resulting from regular hull cleaning. The 18.35% decrease in CO_2 emissions highlights the potential of hull cleaning as a strategy for reducing greenhouse gas emissions, which is critical in the context of global efforts to decarbonize the maritime industry. However, this comes at the cost of increased copper emissions, which introduces a trade-off between climate change mitigation and impact to marine ecosystems. Scenario 4 not only minimizes copper emissions but also achieves the greatest reduction in CO_2 emissions, with a 25.18% decrease compared to the baseline. This dual benefit makes Scenario 4 the most environmentally sustainable option among the strategies analyzed.

This study underscores the importance of a holistic approach to biofouling management, where both emissions to air (CO_2) and emissions to water are considered. The key conclusions drawn from the analysis are:

1. Trade-offs between emissions: The findings illustrate the inherent trade-offs in biofouling management strategies. While regular in-water cleaning of SPC coatings can reduce CO_2 emissions, it leads to a substantial increase in copper emissions, highlighting the need for careful consideration of both types of emissions in environmental impact assessments. A biofouling management strategy will need to consider efficiency savings from coatings, monitoring and maintenance requirements, and the availability and quality of cleaning services.
2. Superiority of silicone-based coatings: Scenario 4, which involves the use of silicone-based low-friction coatings emerges as the most environmentally sustainable option. It significantly reduces both copper and CO_2 emissions, suggesting that silicone-based coatings could play a key role in minimizing the environmental impact of maritime operations for many ship profiles.
3. Policy implications: The results of this study underscore the need for policymakers and industry stakeholders to consider the broader environmental impact of biofouling management strategies. The significant reductions in both copper and CO_2 emissions achieved by silicone-based coatings suggest that regulatory frameworks should promote their adoption. However, the trade-offs associated with in-water cleaning of SPC coatings highlight the need for a more nuanced approach that balances reduced fuel consumption with the potential environmental costs of increased biocide release. Current regulations that emphasize hull cleaning to curb CO2 emissions should be adjusted to support practices that also minimize water pollution, thereby preventing unintended environmental consequences.
4. Future research directions: Further research is needed to explore the long-term environmental impacts of different biofouling management strategies, particularly in relation to the cumulative effects of copper and other particles emissions on marine ecosystems. Additionally, studies that incorporate a broader range of biofouling management options could provide valuable insights into more sustainable shipping practices.

In conclusion, this study provides an analysis of the environmental trade-offs associated with biofouling management strategies. It highlights the importance of considering both air and water emissions in the selection of antifouling coatings and hull maintenance practices, paving the way for more sustainable maritime operations.

Acknowledgement

The opinions expressed are solely those of the authors.

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Biofouling Inspections: A Pillar in Biofouling Management

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Abstract

Biofouling, the accumulation of microorganisms, plants, algae, or small animals on submerged surfaces is a significant concern for the maritime industry. It contributes to the transfer of invasive aquatic species (IAS) across marine ecosystems, disrupting biodiversity and causing substantial economic impacts. The International Maritime Organization's (IMO) 2023 Biofouling Management Guidelines provide structured procedures to mitigate this issue, aiming to prevent the unintentional transfer of IAS from ships' hulls. Despite these efforts, proactive biofouling inspections are under-utilized, even though they have clear potential to enhance environmental and operational efficiency. This article examines the importance of biofouling inspections, particularly from a proactive stand-point, and explores modern inspection tools like remotely operated vehicles (ROVs), Anti-Fouling Systems (AFS), and digital reporting platforms that could revolutionize biofouling management and support vessel optimisation.

1. The Overlooked Importance of Biofouling Inspections

Biofouling inspections are essential for maintaining a clean ship hull, a concept historically under-estimated in maritime operations. Traditionally, biofouling inspections approach have been reactive rather than proactive within ship superintendents and those involved in the management. Vessel operators typically perform inspections only after performance indicators, such as decreased speed or increased fuel consumption, have variations on efficiency. This reactive approach often leads to escalated maintenance costs, reduced fuel efficiency, increased greenhouse gas (GHG) emissions, and the potential transfer of IAS, creating significant operational and environmental impacts.

A study by the Global Industry Alliance for Marine Biosecurity, *GIA (2020)*, revealed that biofouling inspections typically occur after a vessel experiences a 5–10% reduction in speed, indicating severe fouling. This delay results in substantial loss of operational efficiency and increases fuel consumption due to the added drag from biofouling. This 5 to 10% could be detected between weeks months or even years, so the extra fuel consumption could be worth a substantial amount of money and extra GHG emissions.

2. Hull Biofouling Growth and Vessel Operational Profile

Hull biofouling growth is significantly influenced by a vessel's operational profile, including factors such as speed, voyage frequency, port stay duration, and the regions the vessel have operations. Slow-steaming, extended periods of inactivity, and operating in warm waters can contribute and accelerate biofouling accumulation.

- <u>Slow Speed and Idle Time:</u> Ships operating at slow speeds or remaining stationary in ports for extended periods are at higher risk of biofouling. According to a 2024 study by the Global Marine Biosecurity Forum, vessels that reduce their speed to below 10 knots or remain stationary for more than five days can experience a 50% increase in biofouling growth compared to vessels operating at higher speeds or with more frequent transits. This is because low-speed operations allow more time for biofouling organisms, such as barnacles and algae, to attach and grow on the hull surface and niches areas.
- <u>Tropical and Subtropical Waters:</u> Water temperature is another important factor. Vessels operating in tropical and subtropical waters are more prone to rapid biofouling accumulation due to the higher temperature, which accelerates the growth rates of biofouling organisms. Research conducted by *Coutts and Taylor (2022)* found that ships operating in warmer waters can

accumulate biofouling up to 80% faster than those in temperate regions, especially during idle periods in port. Additionally, vessels with frequent calls to biofouling hotspots, such as ports in Southeast Asia and the Caribbean, experience higher fouling rates.

- Port Stay Duration: Long port stays significantly increase the biofouling growth. The same 2024 report highlighted that vessels with port stays exceeding 10 days show nearly twice the biofouling growth compared to vessels with short port calls of less than three days where marine growth is particularly rapid in seawater intakes, rudders, and other areas of the hull that are submerged for long periods.

A study published in *Biofouling (2023)* demonstrated that frequent and sustained high-speed operations (above 15 kn) can help mitigate biofouling growth due to increased water shear forces acting on the hull. Conversely, frequent operation at low speeds (below 10 kn) or extended port stays (more than five days) significantly increase the likelihood of biofouling accumulation.

3. The Impact of Biofouling on Hull Efficiency

Hull efficiency is a critical factor in a ship's overall performance and operating costs. Biofouling adversely affects hull efficiency by increasing the surface roughness of the hull, leading to higher hydrodynamic resistance. This increased resistance requires more engine power to maintain the same speed, resulting in higher fuel consumption and increased GHG emissions.

According to *Schultz (2007)*, even a thin layer of biofilm (slime) can increase the frictional resistance of a ship's hull by up to 10%. When macrofouling organisms like barnacles and tubeworms are present, the increase in frictional resistance can exceed 40%, depending on the extent and type of fouling.

Additionally, the International Maritime Organization reports that heavy calcareous fouling can lead to a 60% increase in hull resistance, which translates to a similar increase in fuel consumption if the vessel maintains its speed. This substantial impact on hull efficiency underscores the importance of proactive biofouling management.

4. Biofouling Inspection

Biofouling inspections are critical for assessing the effectiveness of AFS and for informing maintenance strategies. These inspections typically involve the following elements:

- Inspection Methods
  - Visual Inspections: Routine checks using divers or remotely operated vehicles (ROVs) to visually assess hull conditions and identify early signs of biofouling.
  - Ultrasonic Thickness Measurements: Used to assess the integrity of hull coatings and to detect any deterioration caused by biofouling.
  - Sampling: Collecting samples from the hull and submerged surfaces to analyze the types and amounts of organisms present.
- Frequency of Inspections
  - The frequency of inspections can vary based on operational conditions, such as water temperature, salinity, and the type of routes taken. Regular inspections are recommended to prevent severe fouling that can impact performance.
- Data Recording and Analysis
  - Inspection data is recorded and analysed to track biofouling trends over time. This information is vital for assessing the performance of AFS and for planning maintenance activities.
  - Advanced software platforms can integrate inspection data with environmental parameters to provide predictive analytics.
- Assessment Criteria

- Biofouling inspections often use specific criteria to assess fouling levels, such as the amount of coverage, the types of organisms present, and the impact on hull performance.

- Reporting and Action Plans
  - Inspection results are compiled into reports that outline findings and recommendations. If significant biofouling is detected, action plans may include enhanced cleaning protocols or adjustments to AFS settings.

5. Anti-Fouling systems for Biofouling Control

Below are some of the Anti-fouling systems used on ships for biofouling control.

- Biocidal Coatings (Anti-fouling Paints)
  - Description: These coatings release biocides (such as copper and other chemicals) that prevent the attachment and growth of marine organisms.
  - How it works: The biocides are gradually released from the paint's surface, killing or deterring marine organisms before they can settle.
  - Applications: Widely used on commercial and military vessels. Copper-based paints are-the most common.
- Non-toxic Foul Release Coatings
  - Description: Smooth, slippery coatings made from silicone or fluoropolymers.
  - How it works: They don't prevent fouling organisms from settling but make it difficult for them to adhere. When the ship moves, fouling is easily removed by the flow of water.
  - Applications: Used on vessels where biocidal coatings are restricted due to environmental concerns.
- Ultrasonic Anti-fouling
  - Description: Uses ultrasonic sound waves transmitted through the hull to deter the settlement of organisms.
  - How it works: The ultrasonic waves disrupt the cellular structure of biofouling organisms and prevent them from attaching.
  - Applications: Used on smaller vessels and for niche applications like ballast water treatment
- Electrolytic or Cathodic Protection
  - Description: Systems that use electrical current to prevent fouling and corrosion.
  - How it works: Low-level electrical currents discourage the attachment of marine organisms. In some systems, metal ions are released that create an environment unfriendly to biofouling.
  - Applications: Often combined with biocidal paints or non-toxic coatings, particularly in combination with metal structures like propellers.
- Air Bubble Curtains
  - Description: Continuous streams of air bubbles are released along the ship's hull.
  - How it works: The bubbles create a barrier that disturbs water flow and prevents organisms from attaching to the hull.
  - Applications: Used in dynamic environments or combined with other fouling control systems.
- Copper-Nickel Alloys
  - Description: Copper-nickel materials naturally resist biofouling and corrosion.
  - How it works: Copper in the alloy acts as a natural biocide, preventing the attachment of marine organisms.
  - Applications: Used for specific components like propellers and seawater intakes, though they are more expensive.
- In-Water Hull Cleaning Systems (Rotating Brushes)
  - Description: Mechanical brushes or other cleaning devices are used to remove biofouling from the hull during operation or while the vessel is docked.

    - How it works: Brushes regularly scrub the ship's hull, removing fouling before it accumulates heavily.
    - Applications: Used as a maintenance method to complement anti-fouling paints.
- UV Light Systems
    - Description: UV light is used to prevent biofouling by irradiating surfaces or water systems, killing organisms before they can attach.
    - How it works: UV light damages the DNA of microorganisms, preventing their growth.
    - Applications: Particularly effective in ballast water treatment systems or underwater surfaces.
- Water Jet Systems
    - Description: High-pressure water jets are used to blast away fouling organisms from the hull.
    - How it works: The jets clean the surface by physically removing any growth.
    - Applications: Used for periodic maintenance when ships are in port or in dry dock.

6. Reactive vs. Proactive Inspections: Costs and Risks

Under the current reactive model, ships are inspected for biofouling only when performance metrics suggest an issue. By the time biofouling becomes evident, the hull may already be heavily coated with marine growth, needing expensive cleaning and potentially requiring dry-docking. This reactive method leads to reduced fuel efficiency the added drag from biofouling increases fuel consumption, contributing to higher GHG emissions.

Schultz (2007) quantified the impact of biofouling on vessel performance, concluding that biofouling can increase fuel consumption by as much as 40%, depending on the extent of hull coverage. Additionally, the North Sea Ship Performance Project, *NSSPP (2018),* found that ships with severe biofouling required up to 38% more fuel than vessels with clean hulls.

Effective biofouling management, including regular inspections, can significantly enhance hull efficiency. The Clean Shipping Coalition, *CSC (2019),* highlighted that effective hull maintenance and biofouling management could improve a vessel's fuel efficiency by up to 20%. This improvement not only reduces operating costs but also contributes to global efforts to reduce GHG emissions from shipping, as outlined in the IMO's Initial GHG Strategy.

7. Leveraging Technology: ROVs and Digital Reporting for Cost-Effective Inspections

Innovations in technology offer significant opportunities to improve biofouling management. Remotely operated vehicles (ROVs) are one such advancement. ROVs can perform underwater hull inspections without requiring a diver, making the process safer, faster, and more cost-effective. They can be deployed in most weather conditions, providing high-resolution imaging for detailed assessments of hull conditions. This technology is becoming invaluable in proactive biofouling management strategies.

Studies have highlighted the cost-effectiveness of ROVs, noting that ROV inspections cost 30–50% less than diver-based inspections while reducing inspection time by half. Additionally, ROV inspections can detect biofouling in its early stages, allowing ship operators to take preventive measures before significant performance declines occur.

8. Digital Reporting and Predictive Maintenance

Another vital component of modern biofouling management is integrating digital reporting formats. Using digital platforms to log biofouling inspections streamlines the process of recording and analysing data. This approach allows for seamless sharing of inspection results with ship performance platforms, where the data can monitor trends and predict biofouling growth under specific operational or environmental conditions.

According to a report by the Clean Shipping Coalition, integrating digital platforms with inspection data can reduce maintenance costs by 15% and enhance compliance with international regulations. Predictive maintenance, powered by digital reporting and advanced algorithms, can inform shipowners of the likelihood of biofouling accumulation in certain regions or during specific times of the year. This data-driven approach enables ship operators to plan hull cleanings more efficiently, reducing both time and cost.

9. BMS BIOFLEET Platform

BMS BIOFLEET Platform, Fig.1, acts as a central hub that collects data from several key sources using AI as based to continuously improving quality and reliability. The data includes but not limited to:

- Data Collection Purpose: The BMS BIOFLEET platform gathers this diverse range of information in real-time or periodically to provide a holistic overview of the vessel's environmental and operational conditions.
- Outcome to Fleet Management: After gathering data, the BMS BIOFLEET platform transmits this valuable information to the Fleet Optimisation Team for analysis and for the integration to their system. This allows the fleet to be optimised for several critical areas and have a valuable data of Hull Performance.

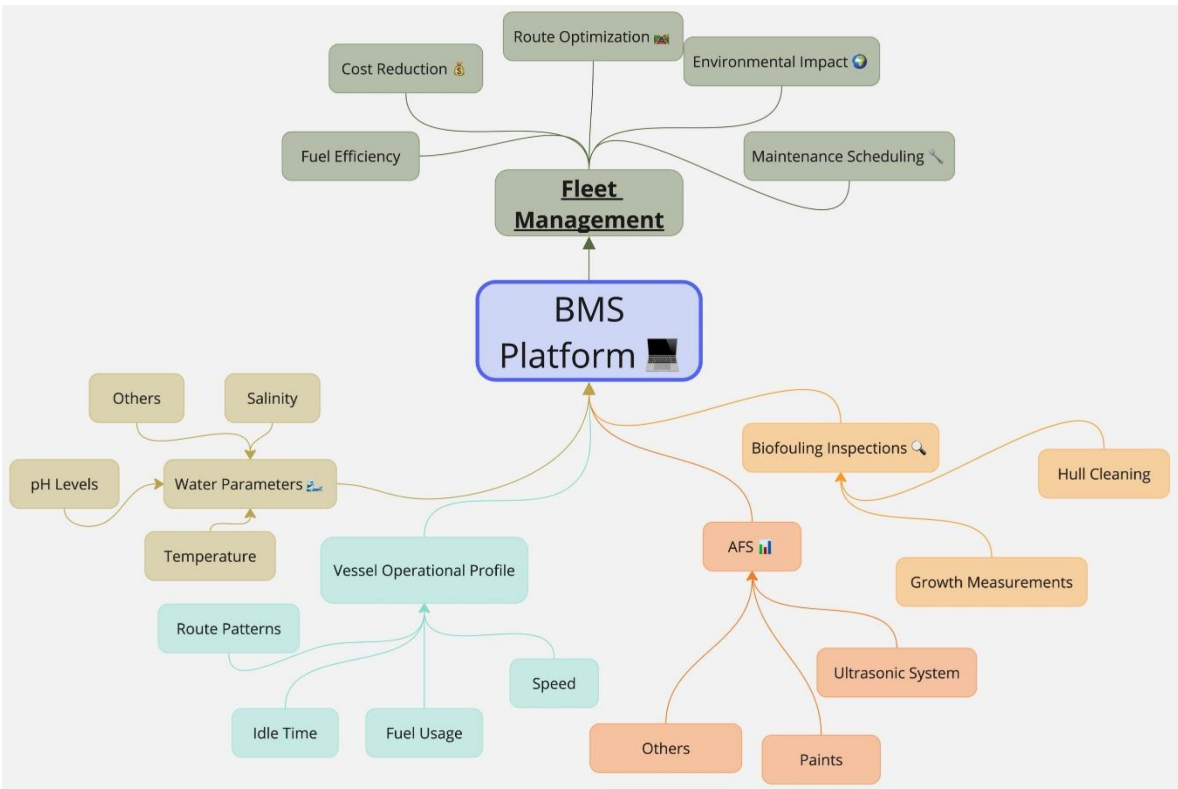

Fig.1: BMS BIOFLEET platform

9.1. BMS BIOFLEET Platform Data Flow

- Data Collection Sources: The BMS BIOFLEET Platform acts as a central hub, collecting data from key sources using AI:
  - Water Parameters: Temperature, salinity, pH levels
  - Biofouling Inspections: Hull cleaning, growth measurements
  - Anti Fouling Systems (AFS): Electrolysis, Ultrasonic, paints, chemical dosing
  - Vessel Operational Profile: Speed, route patterns

- Purpose of Data Collection: The BMS BIOFLEET platform gathers diverse information in real-time or periodically to provide a holistic overview of the vessel's environmental and operational conditions with AI support. This comprehensive dataset is crucial for effective biofouling management.
- Outcome to Fleet Optimisation System: After gathering data, the BMS BIOFLEET platform transmits this valuable information to the Fleet Optimisation Team for analysis. This allows for optimisation in several critical areas:
  - Fuel Efficiency: Improve fuel usage by analysing conditions and optimizing performance
  - Route Optimisation: Determine the best routes based on environmental and operational data
  - Maintenance Scheduling: Ensure preventive maintenance is scheduled efficiently to reduce downtime
  - Cost Reduction: Reduce operating costs through smarter resource allocation and fleet management
  - Environmental Impact: Lower emissions and environmental footprints by aligning vessel performance with sustainability goals

Advantages BMS BIOFLEET Integration data are:

- Enhanced Decision-Making: Real-time data analysis improves decision-making and operational strategies.
- Proactive Management: Combining data with BMS BIOFLEET Platform allows for proactive biofouling management and maintenance scheduling.
- Sustainability: The integration supports sustainability goals by optimizing performance and minimizing environmental impacts.

9.2. Challenges and Considerations

While the integration of AFS, Biofouling inspections and other data to the BMS BIOFLEET platform offers significant advantages, nevertheless challenges and considerations remain. Challenges include:

- Initial Costs: Setup and installation may be expensive, impacting cost-effectiveness.
- Data Quality and Accuracy:
  - Sensors Calibration Issues: The data from water parameters and vessel operations may come from various sensors that require regular calibration. If not maintained correctly, inaccurate readings could lead to faulty decisions.
  - Noise in Data: Raw data, especially from environmental sensors, may have noise or errors. Filtering and cleaning this data is crucial to ensure reliable analysis.
- Inconsistent Data Collection Intervals: Depending on the source (e.g., Sensors vs. biofouling inspections), the data collection may not happen at regular intervals. Inconsistent data could lead to synchronization issues when trying to process or analyse trends.
- Data Gaps: There can be gaps in data collection due to system failures, communication interruptions, or equipment malfunction.
- Redundancy and Duplication: There may be multiple sources providing the same or similar types of information (e.g., water temperature measured by different sensors). Managing redundancy and avoiding duplication of data is a technical challenge.
- Scalability of Data Volume: With multiple sources feeding data continuously, especially from large fleets, the platform might encounter data overload. Handling vast amounts of data and ensuring that key information is processed in a timely manner requires robust infrastructure.

Considerations include:

- Standardization of Data Formats: Ensuring that data from all sources (water parameters, vessel operation profiles, etc.) follow a standardised format is critical. This allows seamless integration into the platform and helps with analysis and reporting.
- Real-Time vs. Periodic Data Collection: Some information needs to be processed in real time, while other data (e.g., biofouling inspections) can be periodic. Prioritizing critical real-time data ensures that immediate actions can be taken.
- Data Validation Mechanisms: Implementing automated data validation mechanisms can help ensure that the information received is accurate and reliable. For instance, cross-referencing temperature readings with weather data could validate sensor accuracy.
- Handling Data Gaps: When data is missing or delayed, interpolation techniques can be used to estimate the values, preventing gaps in the dataset from affecting analysis.
- Security and Integrity of Data: With sensitive data being transmitted (e.g., vessel operational profiles), ensuring secure transmission protocols and data encryption is vital to protect the integrity of the data.
- Scalability and System Performance: As the platform scales to manage data from larger fleets, the infrastructure must be capable of handling increasing volumes of data without sacrificing performance. Efficient data pipelines and storage solutions are important for this.
- Data Feedback Loops: The data collected by the platform can be used to refine and improve the data collection process itself. For example, trends observed in operational profiles may prompt adjustments to how or when certain data is collected.

10. Conclusion

Anti-fouling systems, operational profile and Biofouling inspections, enhanced by the BMS BioFleet Platform, represent a forward-thinking approach to managing biofouling. By leveraging technology and data analytics with AI support, operators can improve efficiency, reduce costs, and align with sustainability goals, ultimately leading to more effective and environmentally responsible marine operations. Continued innovation in this field will be vital for addressing the evolving challenges of biofouling in marine environments.

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6th In-Port Inspection & Cleaning Conference (PortPIC)

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  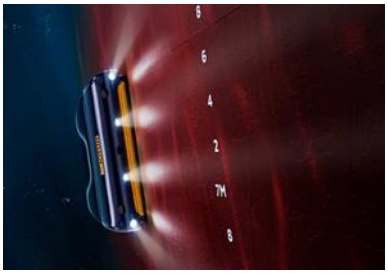

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